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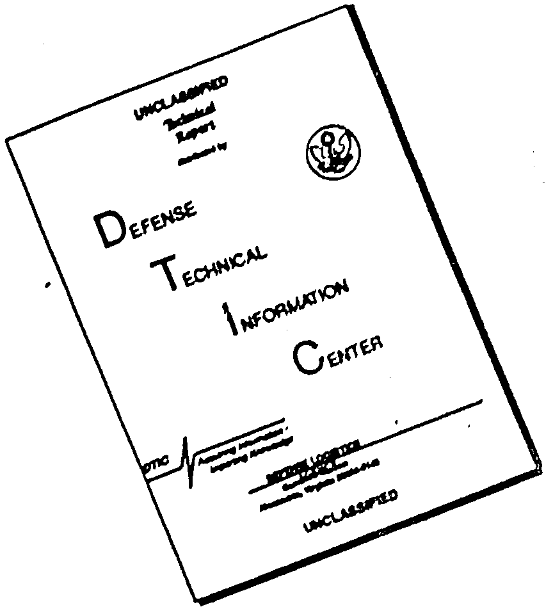

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HYDRONAUTICS, Incorporated

TECHNICAL REPORT 532-1

AIRBOAT NOISE REDUCTION AND IMPELLER DESIGN FOR WATER JET PROPULSION SYSTEMS

By

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PREFACE

This technical study was carried out for the U. S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia, under Office of Naval Research Contract No. Nonr 5018(00) NR 062-371. The study involved an investigation of two different propulsion systems for a shallow draft boat. In the propulsion of this boat by means of an airscrew, the radiated noise is intense enough to cause damage to the ears of passengers and crew. The first part of this study deals with a program to reduce the noise level while delivering the desired thrust. In the propulsion of such boats by means of a water jet, the design of the pump impeller is critical. For a given water jet unit, the maximum thrust that can be developed is dependent on the maximum head that the impeller can develop, which in turn depends on the cavitation characteristics of the impeller. The second part of this study involves the design of an impeller to maximize the thrust of a given water jet system. This report represents the conclusion of all work to be carried out under the contract.

This project was under the overall supervision of Mr. Virgil E. Johnson, Jr., Chief Engineer of HYDRONAUTICS, Incorporated. The work to be done was of such a wide scope that the talents of several personnel of HYDRONAUTICS, Incorporated were utilized. The personnel involved in this project included Dr. Dinshaw N. Contractor, Mr. Otto Scherer, Mr. Eugene Miller, Mr. William Lindenmuth and Mr. Shaikh Matin. The noise and thrust tests were conducted at the Montgomery County Air Park, Gaithersburg, Maryland.

The technical representatives of the U. S. Army Engineer Research and Development Laboratories were Mr. Francis X. Stora and Mr. John Sargent. Mr. Stora's and Mr. Sargent's continued interest and helpful suggestions throughout the entire program were appreciated very much.

INTRODUCTION

The Army has for sometime been interested in developing propulsion systems for small boats that are capable of operating in shallow waters that may be infested with heavy weed growth. Two propulsion systems that show promise for operation in such an environment are water jet propulsion and propulsion with an airscrew. Despite the fact that such systems are satisfactory from a propulsion standpoint, their use creates certain problems which require resolution before successful operational systems are achieved.

In the case of airscrew propulsion, the noise generated by the propeller is a major problem. Since the propeller is close to the personnel in the boat, the high noise levels make speech communication between personnel impossible. Indeed, the noise levels may be so intense as to cause hearing loss of the personnel exposed for any significant time unless some form of ear protection is worn. In addition, the airscrew also radiates considerable sound power to the far field and the presence of the boat can be detected at large distances. Thus, the problem is one of minimizing the noise of the propeller while delivering the same or preferably greater thrust. The description of the research, design and testing program to reduce the airboat noise forms the major portion of this report and is described in detail in the following sections.

In developing water jet systems for use in shallow waters, the Army has procured and tested a water jet system from a commercial firm. Preliminary tests on a boat with the commercial water jet indicated the performance of the unit to be below that anticipated.

The impellers in the water jet unit cavitated earlier than expected, and as a result, the head and discharge decreased and the unit was unable to absorb the installed engine power. Thus, it was desirable to redesign the impellers so that they can deliver a higher head and discharge before cavitating, absorb more of the installed power of the engine and deliver more thrust to the boat. The design of the new impellers is described in a later section.

PRELIMINARY AIR PROPELLER NOISE MEASUREMENTS

Sources of Noise

In the study of the air propelled boat several possible sources of noise were considered. These included the propeller, the engine exhaust, vibration of the boat hull, and vibration of the rudder panels. Preliminary, experimental noise measurements were conducted at Fort Belvoir, Virginia, to assist in identifying the more significant noise sources. The measurements included a survey of the overall sound pressure levels around the boat and frequency analyses of the noise at certain locations. These tests showed that vibration of the boat hull and rudder panels did not contribute any noise. The main sources of noise were the propeller and the engine exhaust. These tests with their results are described below.

The airboat has an aluminum hull, and is about 20 feet long and 8 feet wide. Since it has been designed for high speeds and use in shallow water, it is shaped like a planing boat. The boat is powered by a 400 horsepower, 8 cylinder, Lycoming engine, with a maximum rpm of 2650. The engine was calibrated so that knowing

the suction manifold pressure and the rpm, the horsepower delivered by the engine could be determined. The engine had no muffler when the preliminary tests were conducted. This engine drove a 4 bladed, wooden, pusher-type propeller.

The airboat was towed to a level field in which there were few obstructions. The noise measurements made around the airboat utilized instruments manufactured by General Radio Company. The noise was picked up by a piezoelectric microphone, which had a flat frequency response to 8000 cps. The microphone output was supplied to a sound level meter, from which the overall noise level could be read. The output of the sound level meter was supplied to the wave analyzer and a graphic level recorder was used to record the wave analysis of the noise. A constant bandwidth of 50 cps was used to record the frequency distribution of the noise. The instrumentation was calibrated with a 120 db, 400 cps tone provided by a calibrator placed over the microphone. Figure 1 shows photographs of the airboat on the trailer and the noise instruments used.

Figure 2 presents the overall noise level variation around the airboat, with the engine running at 2600 rpm. Table 1 presents the maximum acceptable steady state noise levels recommended for Army Material Command Equipment. The overall level measured at the driver's seat is 127.5 db, which is far greater than the recommended overall level of 121.7 db. During the course of the noise tests, all personnel wore ear protectors as a necessary safeguard. Figure 3 shows the frequency distribution of the overall noise at one location. It can be seen that the peaks occur at the propeller

TABLE 1

Octave Band Limits cps	Sound Pressure Level in db(re.0.0002 dynes/cm^2)
37.5 - 75	120
75 - 150	115
150 - 300	109
300 - 600	101
600 - 1200	93
1200 - 2400	89
2400 - 4800	89
4800 - 9600	91
Overall	121.7

blade passage frequency and its harmonics, indicating that propeller noise is a predominant source. The engine exhaust noise occurs at the average firing frequency of the engine and in this case, this frequency happens to coincide with the fundamental propeller frequency. Thus, it is difficult to distinguish between the relative importance of each source. It is, of course, obvious that mufflers should be used and that they will be helpful in reducing the noise level. However, it is important that the correct muffler be used so that noise attenuation will be obtained at the right frequencies. Thus, when two truck mufflers were used on this engine, no significant reduction in noise resulted. The manufacturer of the aircraft engine, however, did recommend a muffler system, available from the Piper Aircraft Corporation. This

muffler system was installed in the boat and new noise measurements conducted. Significant noise reductions were obtained. Details of these tests are presented in a subsequent section of this report.

With the use of the correct muffler, it became apparent that the propeller was the major source of noise and the entire program was directed to reducing the propeller noise while delivering the same thrust.

THEORETICAL NOISE ANALYSIS

The noise radiated by a propeller operating in free space can be divided into three components, (a) Rotational Noise, (b) Vortex Noise, and (c) Thrust and Torque fluctuations due to a non uniform inflow to the propeller disk. The rotational noise is due to the steady state thrust and torque developed by the propeller and is associated with the pressure field that rotates with the propeller. This noise occurs as sharp peaks at discrete frequencies, these frequencies being the blade passage frequency and its harmonics. Vortex noise is due to the unsteady aerodynamic forces on the blades associated with the shedding of vortices in the wake of the blades. These unsteady forces which give rise to thrust fluctuations, occur over a wide band of frequencies, with the peak occurring at a Strouhal number of 0.2.

A propeller can also radiate noise when operating in non-uniform inflow. Such inflow conditions can be created by the wake of objects (e.g. struts) ahead of the propeller disk and by the proximity of solid boundaries to the tip of the blades. The inflow conditions cause the blade to see variations in the angle of attack,

giving rise to fluctuations in the thrust and torque. These fluctuating forces act as dipole sources of sound. The thrust dipole radiates sound along the propeller axis and the torque fluctuations propagate in the plane of the propeller disk. The frequency of these fluctuations is equal to a constant times the blade passage frequency, where the constant depends on the nature of the inflow conditions. The intensity of such fluctuations is, however, difficult to determine. One of the parameters on which it would depend is the blade area ratio. This fact was helpful in guiding the course of experiments later in the program.

Rotational Noise

A theoretical analysis of the rotational noise of a propeller operating in free space and at zero forward speed is presented in Reference 1. This analysis gives the far-field sound pressure of different harmonics as a function of the geometry and aerodynamic performance of the propeller and the location of the observer. The following formula is the result of the analysis:

$$p_m(r,\theta) = \frac{mn\omega}{2\pi cr}\left[-T\cos\theta + \frac{cQ}{\omega R^2}\right] J_{(mn)}\left(\frac{mn\omega}{c} \times .75\,R\sin\theta\right) \qquad [1]$$

where

$p_m(r,\theta)$ = Sound pressure of the m^{th} harmonic at location (r,θ),

T = Static thrust of propeller

$= [2\pi\rho R^2 P^2 \eta^2]^{\frac{1}{3}} = [\pi\rho R^2 P^2 C_M{}^2]^{\frac{1}{3}}$,

P = Power absorbed by propeller,

Q = Torque of propeller,

ω = Angular speed of propeller,

R = Radius of propeller,

m = Order of harmonic,

n = Number of blades on propeller,

$$C_M = \frac{T^{3/2}}{\sqrt{\pi\rho R^2}\ P} ,$$

$$\eta = \text{Static Efficiency} = \frac{T^{3/2}}{\sqrt{2\pi\rho R^2}\ P} = \frac{C_M}{\sqrt{2}} ,$$

c = Speed of sound,

r = Distance of observation point from propeller disc center,

θ = Angle between radius r and forward direction of propeller, and

$J_{(mn)}$ = Bessel function of order (mn).

The calculation of sound pressures from Equation [1] gives slightly lower sound pressures than experimentally measured, see Reference 2. However, the analysis is very helpful in understanding the relative importance of different parameters and in establishing the directivity of the sound radiation and provides some guidance for the rotational noise reduction program. Thus, a few general observations will be made on the information obtainable from Equation [1], which will be useful in interpreting the experimental data.

(a) The sound pressure is zero along the propeller axis and reaches a maximum just behind the plane of the propeller.

(b) For a small number of blades, the first harmonic contains the greatest energy and the higher harmonics contain smaller amounts of energy. For a large number of blades, the higher harmonics may be as intense as the fundamental.

(c) For a given number of blades, the acoustic level rises sharply with tip Mach number and for a given tip Mach number the acoustic level decreases as the number of blades is increased.

Vortex Noise

Vortex noise is associated with the shedding of vortices in the wake of the blade. The strength of these vortices is low when they are caused by the boundary layer on the foil. When the flow about the foil separates, the strength of these vortices is greatly increased. These vortices cause fluctuations in the lift of the

blade and consequently the thrust of the propeller. These fluctuating forces give rise to acoustic dipoles, that radiate sound with a peak intensity along the axis of the propeller and with zero intensity in the plane of the propeller. No theory exists to predict the vortex noise of a propeller accurately. However, some analysis and experiments have been performed on cylindrical rods rotating about the center of the rod. The mechanics of sound generation and the pattern of radiation are identical for the rods and actual propeller blades. Reference 3 derives an equation for the total acoustic power, P_A, radiated by the rods as a function of geometry and speed and is presented below.

$$P_A \propto (C_D S)^2 \frac{\rho V_t^{\,6}}{c^3} R \; d \qquad [2]$$

where

C_D = Form drag coefficient of rod section,

S = Strouhal number = fd/V_t,

V_t = Tip speed,

c = Speed of sound in medium,

R = Distance of rotating axis to tip, and

d = Diameter of the rod.

In the case of the propeller, the term d to be used is the projection of the vane profile normal to the relative velocity past the section. It is also shown in Reference 3 that the total acoustic power of the vortex sound increases in proportion to the

square of the linear dimensions of the rod for a given tip speed. This suggests that the acoustic power of vortex noise is directly proportional to the blade area ratio (BAR) of the propeller. These observations will be very helpful in interpreting the test results of propeller noise.

For conventional propellers, vortex noise dominates over rotational noise only at low tip Mach numbers. At higher Mach numbers, say $M_t > 0.6$, rotational noise will be greater than vortex noise, since rotational noise increases at a faster rate than vortex noise with tip velocity. However, in the case of propellers with a very large number of blades vortex noise may be as intense as rotational noise because of the large blade area ratio of the propeller.

Theoretical Noise Reduction

Assuming that rotational noise predominates, the methods by which the noise of a propeller can be reduced, are obtained from Equation [1]. There are three methods by which a propeller could be designed to radiate less noise.

(a) For a given number of blades, the lower the tip Mach number, the lower will be the noise output. Thus, the diameter and the rpm of the propeller should be selected in such a way as to keep the tip Mach number as low as possible, while still delivering the design thrust. This requirement leads to large diameter, slow turning propellers. For the given airboat, the size of the propeller could not be increased significantly because of

the engine mounting and arrangements. As a result, the remaining methods of noise reduction were found to be more suitable in the present case.

(b) The rotational noise of a propeller is reduced by using a larger number of blades with the same total BAR. For a given thrust and blade lift coefficient, the blade chord required by aerodynamic design decreases with increasing number of blades such that the blade area ratio remains the same. A limit on the allowable number of blades is reached when the blade chords become so small that they are not structurally adequate. To make the blades structurally adequate, the blade chords have to be increased, thus increasing the BAR. The higher BAR increases the vortex noise and the wake induced noise, thus partially nullifying the advantage of using a large number of blades.

In order to help in the design of new propellers, Equation [1] has been rewritten in terms of the tip Mach number, $M_t = \frac{\omega R}{c}$, and the number of blades, n. The speed of the propeller is held constant at 2600 rpm and it is assumed that the BAR is sufficient to absorb 400 horsepower. The following values are used in the calculation of sound pressure p from Equation [1],

$\rho = .00238 \text{ lbs/ft}^3$ $\qquad$ $c = 1117 \text{ fps.}$

$P = 400 \text{ horsepower}$ $\qquad$ $R = 3.25 \text{ ft.}$

$$\omega = \frac{2\pi N}{60} = \frac{2\pi 2600}{60} = 272 \text{ rads/sec.}$$

$\eta = 0.8$ (assumed) $\qquad$ $T = 1696 \text{ lbs.}$

$r = 25 \text{ ft.}$ $\qquad$ $\theta = 120^{\circ}.$

Using these values, Equation [1] has been reduced to the following form,

Sound pre sure level, SPL, in db (re.0.0002 μ bars)

$$= 117.2 - 20 \log_{10} \left\{(n-1)!\right\}$$

$$+ 20\left[n \log_{10}(.325\ n\ M_t) + \log_{10}\left(4.67\ M_t^{\frac{2}{3}} + \frac{1}{M_t^{2}}\right)\right]$$

Results obtained from this equation are plotted in Figure 4. From this figure, a suitable choice of the number of blades and tip Mach number can be made to give an acceptable rotational noise level. It is not possible to evaluate the vortex noise levels as reliably as the rotational noise levels. From Figure 4 it was decided that a propeller with 16 blades would be designed. The details of the design of this propeller are presented in the next section.

(c) A third method of reducing the noise level suggested in Equation [1] is to design propellers with a large value of static efficiency, η, or figure of merit C_M. With a large value of η or C_M a given thrust can be achieved with a lower power input and hence the noise due to the steady-state torque (the second term in Equation [1]) is reduced. However there is a very real limit to the values of η or C_M that can be obtained with conventional propellers. Another way of increasing C_M is by the use of a shroud or nozzle around the propeller. The use of a good shroud can increase C_M by 50-100 percent. The use of a well designed shroud to

reduce the sound level of a propeller is discussed in Reference 4. Thus, it was decided to design a shroud, so that part of the required thrust could be developed on the shroud and thus the propeller loading could be relieved. As a result less propeller noise should be generated. The design of the shroud and its fabrication are also described in a subsequent section.

PROPELLER DESIGN

The importance of increasing the static efficiency (η) or the figure of merit (C_M) was discussed in the previous section. These coefficients are primarily dependent on the geometry of the propeller and its surroundings and are defined below.

$$\eta = \frac{C_M}{\sqrt{2}} = \frac{T^{3/2}}{PR\sqrt{2\pi\rho}} \qquad [3]$$

It can be seen from this relation that for a given engine power and rotational speed the thrust delivered is proportional to $R^{\frac{2}{3}}$. However, increasing propeller radius for a fixed rotational speed increases the tip Mach number and, as previously discussed, this will increase the noise level.

It is of interest to examine the performance of different diameter propellers driven by the existing engine and operating at the same tip Mach number. The maximum engine torque is essentially constant and independent of rotational speed. (i.e. power is proportional to engine RPM). The value, η, can be rewritten in terms of engine torque and tip speed by noting that:

$$P = \omega Q$$

$$V_t = \omega R$$

Substituting these into [1],

$$\eta = \frac{T^{3/2}}{QV_t\sqrt{2\pi\rho}}$$

This relation shows that the thrust is independent of diameter if η, Q, and V_t are all constant. In fact, Equation [3] shows that the required engine power will vary inversely as the propeller diameter. It should also be pointed out that as the diameter is increased, the static efficiency is likely to increase because the engine nacelle will obstruct a smaller proportion of the total propeller disc. Thus, the required power for a given thrust will be further reduced as the diameter is increased. The reduced power loading for the larger diameter propeller will, of course, lead to quieter operation for a given thrust and tip speed.

It is therefore clear that the largest practical propeller will yield the best results from the standpoint of both efficiency and noise. A 6.5 foot diameter propeller for the present applications was selected as this was the largest diameter propeller that could be mounted with the existing engine installation. (The removal of flanges at the base of the engine mount now permits the installation of a slightly larger propeller.)

As previously mentioned, a further increase in performance is obtained by replacing the bush-guard with an accelerating shroud. The detailed design of the shroud is discussed in the next section. For the purpose of designing the propeller it was assumed that the shroud would produce 10 percent of the total thrust.

The noise theory discussed earlier indicated the desirability of a 16 bladed propeller. Strip theory was used to determine the blade geometry that would give the best overall performance. The resulting design represents a compromise between the conflicting requirements of quiet operation, good static thrust, good performance at cruise speed, and adequate blade strength.

A propeller was designed to absorb 390 horsepower under static conditions while operating at 2600 rpm within the nozzle. This propeller has an 18 inch diameter hub and is 6.5 feet in diameter. It was calculated that the nozzle propeller system would deliver a total static thrust of 1625 pounds with the propeller producing 1462 pounds. This corresponds to a static efficiency of 0.8 and a figure of merit of 1.13. Figure 5 shows the predicted variation of total thrust with forward speed while the blade planform and airfoil sections are shown in Figure 6. Figure 7 shows the radial distribution of chord length, thickness, and blade angle.

To obtain good static efficiency the propeller blades should operate at a lift coefficient that will produce the best lift-drag ratio at each radial station. They should also be proportioned to produce nearly constant loading over that portion of the propeller disc that is not in the wake of the engine. In this case, these considerations demand a low blade area ratio and blades that are tapered with decreasing chord toward the tips.

A low blade area ratio is also desirable because it makes the propeller thrust less sensitive to changes in inflow velocity. This is advantageous for several reasons: (1) the thrust will not diminish as rapidly as forward speed is increased, (2) the thrust will be less affected by gusting winds, this is especially important when maneuvering at low speed, and (3) the thrust fluctuations caused by the blades passing through the engine mount wake will be maintained, thus minimizing this source of noise. However, to obtain adequate blade strength in a propeller with 16 blades while keeping an acceptable chord-thickness ratio requires the blades to have larger chords than would be desirable from purely aerodynamic considerations. This would not be the case if the propeller had eight or fewer blades.

A final consideration is the blade section critical Mach number. An airfoil traveling at high subsonic Mach numbers may have regions of local supersonic flow. This is due to the increase in local velocity as the air passes over the foils. The speed at which this first occurs is a function of both airfoil shape and lift coefficient and this velocity divided by the speed of sound is referred to as the "critical Mach number". At speeds above the critical Mach number small "shocklets" are formed near the foil surface. Since the main flow is subsonic these shockwaves will not propagate beyond the region of local supersonic flow and thus do not contribute directly to the overall noise level. However, they could impinge on the nozzle or deck causing these to vibrate and radiate additional noise. In addition, the blade drag coefficient usually increases at speeds above the critical Mach number which

will, of course result in a loss of efficiency. It is therefore desirable to select a blade section and angle of attack that will yield a high critical Mach number for the blade tips.

The NACA 63_2-412 section was selected as the optimum section for the blade tips of the present design. It has both a high critical Mach number extending over a wide range of lift coefficients and relatively low drag. Figure 8 shows the relation between the critical Mach number and the tip Mach number over the range of operating lift coefficients. It can be seen in this figure that the blade tip speeds exceed the critical speed at full throttle rpm. However, their speed will probably be subcritical at normal cruising speeds and this will help reduce noise.

Unfortunately the cost of machining 16 of these blades for an experimental propeller was prohibitive so commercial light plane propeller blades were substituted. The blades most nearly matching our design are the Hartzell model 7636-4 (left-handed) blades. These are made of 2025 ST-6 forged aluminum alloy and are anodized. These blades are somewhat larger than desirable and, being designed for use on a smaller hub, have too much radial twist. The table compares blade chords and pitch angles at four radial stations.

Radius (inches)	HYDRONAUTICS, Incorporated Blade Design		Hartzell Blades	
	Chord (inches)	Pitch (deg)	Chord (inches)	Pitch (deg)
12	4.70	27.13	4.85	25.8
21	3.80	19.40	5.91	18.3
30	2.90	13.25	5.18	12.0
39(tip)	2.00	10.13	3.40	6.8
	Blade Area Ratio = 0.336		Blade Area Ratio = 0.484	

The excessive radial twist is particularly damaging to the performance since it unloads the blade tips which decreases the effective propeller diameter and reduces the performance of the shroud.

It was desirable to keep the hub as small as possible so that the engine cooling air would not be unduly restricted. With a slight modification to the blade shanks it was possible to mount the 16 blades on a 17-3/8 inch diameter hub, as compared to the 14-1/2 inch diameter hub on the current 4 bladed propeller. The blades can be easily removed from the hub and their pitch can be adjusted. This flexibility permits full throttle torque to be absorbed at various engine speeds and with various numbers of blades. Since the new propeller and the original propeller have the same diameter and hub thickness they are interchangable without modification to the engine and hub assembly. The assembled propeller weighs 325 pounds with each blade weighing 11 pounds. While this is heavier than desirable it was felt to be acceptable for the present test purposes. Figure 9 shows the assembled propeller in the shop and mounted on the airboat. Figure 10 shows the propeller with the shroud installed.

SHROUD DESIGN AND CONSTRUCTION

A shroud was designed and constructed for installation on the airboat. There are a number of factors which influence the selection of shroud geometry and arrangement on the boat. Some guidance for the development of the proper section shape and location with respect to the propeller is presented in Reference 5. However, because the propeller is so heavily loaded in the static condition,

a theoretical solution for the optimum shroud geometry is subject to considerable uncertainty. The theory does indicate that the function of the shroud is to prevent the constriction of the propeller slip stream. As a result, in the ideal case the propeller should be placed reasonably near the leading edge of the shroud. Also, the tip clearance between the propeller and the shroud should be made as small as possible. An estimate was made of the geometry of a shroud which would satisfy the above conditions. This shroud is shown in Figure 11. There are, however, a number of practical arrangement problems which prevent a shroud of this geometry from being installed on an existing airboat. The major problem is that the propeller is located very near the transom of the boat. Thus any shroud which extended far enough past the propeller would interfere with the rudders and with the handling of the boat. There would also be a structural problem because of the very limited area in which to attach the shroud to the hull structure. Because of these considerations it was necessary to install the shroud forward of what would have been the ideal location. The shroud as installed on the boat is also shown in Figure 11.

An arrangement drawing showing the details of the shroud construction and installation on the boat is enclosed as Figure 12. The overall diameter of the shroud is 8'-10" and the inside diameter is 7'-0". The chord length is 30-3/8 inches and the maximum thickness is 6-7/16 inches. The construction of the shroud is composite aluminum and fiberglass. The inner skin of the shroud is fiberglass reinforced epoxy with a thickness of 3/16 inch. This skin is bonded to tubular aluminum leading and trailing edge

members and to an aluminum plate spar. The outer surface of the shroud is 1/32 inch sheet aluminum. The shroud is filled with a fiberglass blanket of about 1.5 lb/ft^3 density to provide acoustic absorption. The offsets for the section profile and the structural arrangements described above are shown in HYDRONAUTICS, Incorporated drawing number 532-4 enclosed as Figure 13. The weight of the shroud is about 230 pounds.

DESIGN OF TWIN ENGINE AIRBOAT

The contract also called for investigation of a twin engine airboat to provide the same thrust and performance as the single engine airboat. Such a design should be quieter and improve the stability of the boat. An extensive study was made of the engines available for use on this craft. Based on weight, power and shaft rpm, two Lycoming HIO-360-A1A engines of 180 horsepower each are the most suitable for this installation. The weight of this type of aluminum boat would increase from 2750 pounds for the existing single 400 horsepower engine installation to 2840 pounds with twin engines totaling 360 horsepower. The center of gravity will move aft about .15 feet and down about .25 feet as compared with the existing single engine boats. This should improve the stability of the boat slightly.

HYDRONAUTICS, Incorporated drawing No. 532-9 showing the general arrangement of the design is enclosed as Figure 14. The arrangement drawing shows the engine fitted with 4.5 foot diameter unshrouded propellers. These provide about the same propeller disc area as the single 6.5 foot diameter propeller on the single engine boat. Thus the static thrust and overall performance of the

twin engine boat should be about the same as the single engine boat. However, because of the smaller diameter of each propeller the noise level and the profile height will be reduced. The twin engine craft will be more maneuverable and reliable than the single engine craft. Kick-up underwater rudders are shown on the enclosed arrangement drawing. These will be necessary to control the boat when running on a single engine. The moment due to off-center thrust would be too large for the air rudder alone to overcome. With underwater rudders it was estimated that the boat at 5000 pounds displacement could make about 18 knots on a single engine.

A study of the noise characteristics of the two propellers showed that the rotational noise could be decreased by 6-8 db because of the lower tip Mach numbers encountered in this design. However, the machinery arrangements for the twin-engine design will require extensive modifications to the present airboat. The engines required to propel such a craft were procured in accordance with the provisions of the contract in anticipation of the intention of the sponsoring office to continue the present contract to build and test the twin engine craft.

EXPERIMENTAL TESTS

The propeller and nozzle, described in the previous sections, were tested for noise and performance extensively. A summary of the different conditions of the tests is given in Table 2. A detailed description of the tests and an analysis of the test results is presented in the following sections. At the end of these

TABLE 2

Summary of Test Conditions

Propeller Description				Shroud	Remarks
Diameter	Number of Blades	Blade Pitch at 0.7 R	RPM		
6'6"	4	13.5°	2575	Without	Original wooden propeller
6'6"	8	6°	2850	Without	All the remaining tests were made with the newly designed aluminum propeller
		8°	2600	Without	
		10°	2380	Without	
		12°	2150	Without	
6'6"	8	6°	2900	With	
		8°	2700	With	
		10°	2475	With	
		12°	2275	With	
6'6"	16	8°	2475	Without	
		10°	2200	Without	
		12°	1850	Without	
6'6"	16	8°	2575	With	
		10°	2450	With	
		12°	2150	With	
		14°	1850	With	

tests, it was concluded that the nozzle was not performing as expected; i.e. the thrust of the propeller-shroud combination was lower and the noise greater than that of the propeller alone. Consequently, a series of model tests were made to determine the best method of improving the effectiveness of the shroud. These model tests, which are described in detail in a later section, indicated that the shroud could be made more effective by reducing the clearance between the tips of the blades and the inside of the shroud. Consequently, the blades of the prototype propeller were extended to a diameter of 6'11", thereby reducing the tip clearance from 3" to 1/2". The series of prototype tests conducted with this modified propeller in the shroud is presented in Table 3.

NOISE AND PERFORMANCE TESTS OF PROPELLER AND PROPELLER-SHROUD COMBINATION

Prototype noise and performance tests were conducted at Montgomery County Air Park, Gaithersburg, Maryland. This site was chosen because it afforded a flat, wide-open area where sound would not be reflected from trees or buildings. Also, aviation gasoline and personnel for proper operation and maintenance of the engine were readily available.

Static thrust was measured by a spring dynamometer. The test configuration is shown schematically in Figure 15. The carriage was placed on wooden planks so that it would roll smoothly. The dynamometer was read while the boat carriage was rolling both forward and aft. The two readings were then averaged to give the true thrust. The rolling friction of the carriage and cable pulley

TABLE 3

Experimental Test Conditions

Propeller Description					
Diameter	Number of Blades	Blade Pitch at 0.7 R	RPM	Shroud	Remarks
6'11"	8	8° 10° 12° 14°	2650 2650 2450 2200	With	Blade tips were extended by 2-1/2"
6'11"	4	10° 12° 14°	2650 2650 2550	With	
6'11"	2	10° 12° 14° 16° 18°	2650 2650 2650 2450 2250	With	

was thereby eliminated. Engine rpm and intake manifold pressure were also recorded. These readings were then used with the calibration curve supplied by the engine manufacturer to obtain shaft power, P.

Noise and performance tests were conducted concurrently. Total sound pressure levels, SPL, were measured and recorded graphically. The measurements were made at several stations around the boat. These stations were all at a 50 foot radius from the propeller hub and spaced at 22-1/2° increments from 0° (directly ahead of the boat) to 135° (off the stern quarter). The wake of

the propeller prevented making measurements at 157-1/2° and 180° (directly astern). Noise frequency analyses were made with a General Radio Variable bandwidth frequency analyzer, type 1900 A. The SPL was recorded automatically as a function of frequency on strip-chart paper. These frequency analyses were generally recorded only for the 0° (directly ahead) and 90° (abeam) stations.

Tests were made for several propeller configurations which are described here briefly.

> Four bladed wooden, 6.5 ft. diameter propeller. This propeller came with the airboat and its performance was considered to be a reference with which to assess the performance and noise reduction of the remaining configurations.

> 6.5 ft. diameter aluminum propeller and hub with 4, 8, and 16 blades. The pitch of the blades was varied from 8° to 14° at 70 percent of the tip radius.

> 7 ft. diameter shroud and 6.5 ft. diameter propeller with 4, 8, and 16 blades. The same propeller and hub as above was used with the addition of a fiberglass shroud around the propeller.

The results of the performance tests are presented in Figures 16, 17 and 18. These figures show thrust, maximum rpm, horsepower, and the dimensionless figure of merit, C_M for the various propeller configurations. They are plotted as functions of the blade pitch at the .7 tip radius measured in degrees.

Results of noise tests are presented in Figures 19 through 24. Figures 19, 20, 21 and 22 show total SPL in db (re.0.0002 μ bar) for the various propeller configurations at a 50 foot radius from the propeller hub. Figures 23 and 24 show frequency analyses of two propeller configurations. Here, the SPL is plotted as a function of frequency. The principal conclusions to be drawn from these tests are:

(i) The 4 bladed wooden propeller provided a thrust of 1100 pounds and the noise levels around the boat (refer to Figure 19) are lower than the levels measured at Ft. Belvoir. This change is due to the fact that the mufflers recommended by the engine manufacturer were used in these tests. These lower noise levels were taken to be the reference levels. The noise levels of the new propellers are compared with this reference level to determine their effectiveness in noise reduction.

(ii) As seen in Figure 18, the 16 bladed propeller did not produce 1100 pounds of thrust either with or without the shroud at the pitch angles tested. Hence, no valid comparisons of the noise levels could be made with the 4 bladed wooden propeller. The noise levels with the shroud are greater than those with the propeller alone as seen in Figure 22. This is due to the fact that the flow separates from the inside of the shroud.

(iii) As seen in Figure 17 the 8 bladed propeller produced a maximum of 1225 pounds of thrust without the shroud and 1100 pounds of thrust with the shroud. At the higher blade pitches,

the 8 bladed propeller was slightly quieter than the 4 bladed wooden propeller. However, the noise levels were still high and because of the separation of the flow from the inside of the shroud, it was concluded that the nozzle was not being used effectively.

MODEL TESTS

Results of the thrust and noise tests on the prototype indicated that the propeller-shroud configuration was not performing as anticipated. Flow studies with yarn tufts on the inner surface of the shroud showed that the flow was separating from the shroud inner surface ahead of the propeller. The maximum figure of merit C_M, obtained was approximately .75 compared with theoretical indications that shrouded propellers can yield values C_M as high as 1.7. It was concluded that modifications should be made on the shroud-propeller configuration to eliminate flow separation, increase the figure of merit and, thereby, reduce noise. Scale model tests were determined to be the most expeditious method of studying various changes in shroud design.

A one to 9.33 scale model was fabricated at HYDRONAUTICS, Incorporated. This model is shown in Figure 25. A 1/2-horsepower AC-DC series motor was chosen to drive the model airplane propeller. The size of the motor was such that it modeled the blockage caused by the prototype aircraft engine with fair accuracy. The shaft horsepower of the motor was calibrated as a function of motor rotative speed with a torsion dynamometer. Several model airplane propellers (2- and 4 bladed) with different pitches were used to vary the model thrust. The thrust of the shroud and propeller were measured separately with two thrust dynamometers

which are shown in Figure 25. Rotative speed was measured with a stroboscope (Strobotac). The figure of merit, C_M, is calculated from

$$C_M = \frac{T^{3/2}}{(\rho A)^{\frac{1}{2}} P}$$

where

T = total thrust in pounds,

ρ = density of air,

A = disc area of model propeller, and

P = power in ft-lbs/sec.

Four basic model configurations were tested: the propeller alone, the propeller with a block to simulate the boat-stern, the propeller with a complete shroud, and the propeller with a shroud mounted on a block to simulate the boat stern as shown in Figure 26. Various modifications and alterations were tested on one or more of the basic configurations and are described briefly as follows: a leading-edge ring splitter plate on the shroud; a modified shroud shape with increased chord; variation of fore and aft placement of the shroud with respect to the propeller plane; various diffuser configurations attached behind the shroud; and variation of tip clearance between the propeller and the inside of the nozzle. A more detailed description of these tests and the results is found in Reference 6. Of the modifications tested, reducing the tip clearance provided the best means of increasing C_M. Figures 27

and 28 show the results of model tests with variation in tip clearance (values of tip clearance are given to prototype scale). Figure of merit C_M is plotted as a function of model propeller pitch-diameter ratio P/D. The dashed line in each figure is the result from tests of the propeller without shroud and corresponds to the diameter necessary for 3 inch prototype tip clearance. It can be seen in these two figures that the value of C_M can be increased 25 to 30 percent by reducing tip clearance from 3 inches to 3/4 inch. The effect of the boat-end is to decrease C_M slightly from those values for a complete shroud around the propeller.

Figure 29 shows that the behavior of model and prototype are similar. In Figure 29 the figure of merit, C_M, is plotted versus pitch-diameter ratio P/D.

VIBRATION STUDIES

The scale model tests described in the previous section indicated that a reduction in tip clearance between the propeller blades and the nozzle would result in considerable improvement in static thrust and figure of merit, C_M. The minimum acceptable tip clearance in the prototype should allow operation of the boat under all anticipated operating conditions without danger of contact between the blade tips and the shroud. It was necessary to determine the maximum relative motion between the propeller and shroud under different operating conditions in order to specify a minimum allowable clearance. Vibration studies were made on the prototype to evaluate the maximum deflection of the shroud relative to the propeller.

Polyurethane foam blocks were mounted inside the shroud in the propeller plane at several positions around the shroud. The blocks were shaved until they had zero clearance with the blade tips. Any relative motion between the rotating propeller and shroud caused the propeller tips to "machine" a groove in the foam blocks thus providing a record of the maximum relative motion.

It had been noted during earlier noise tests of the prototype that the largest deflection or vibration of the shroud occurred when starting or shutting down the engine. It was found that this is also the time when the maximum relative motion occurs between the propeller and shroud. However, it was noted that the maximum relative motion (3/16") was much less severe than the absolute excursions of the motor and shroud as a unit (about 1-1/2 inches).

Relative and absolute motion of the shroud and propeller at normal operating rpm was found to be negligible. Personnel jumped on the decks in an attempt to simulate slamming of the hull, but no relative motion could be detected.

It was concluded from these studies that a nominal tip clearance of 1/2 inch would be acceptable and that the shroud should be more carefully aligned with the propeller centerline to assure a minimum tip clearance of 3/8 inch. It was concluded that further reduction of tip clearance would yield diminishing returns in performance while greatly increasing the possibility of damage to the shroud and propeller. The tip clearance was reduced from 3 inches to 1/2 inch by welding aluminum extensions to the tips of

the blades. The extensions were then milled down to the tip airfoil section without any further twist in the blade. The modified propeller was thus 6'11" in diameter, while the inside of the shroud remained 7 inches in diameter.

NOISE AND THRUST TESTS OF MODIFIED PROPELLER-SHROUD COMBINATION

The modified propeller-shroud combination consists of the 6'11" propeller installed in the shroud with a tip clearance of 1/2 inch all around the shroud. The first series of tests were made with 8 blades mounted on the propeller hub. These tests showed that the vortex and wake-induced noise made up a large part of the total noise. Increasing the number of blades to 16 would have doubled the blade area ratio and increased the vortex and wake-induced noise. Thus, further tests were made with 4 and 2 blades mounted on the hub. The tests included measurements of the noise and the static performance of these propellers at various pitches. At each pitch, the noise and thrust measurements were made for two different conditions. First, the tests were conducted with the engine running at full throttle or at the maximum allowable engine speed of 2650 rpm. Under these conditions, it was noticed that the measured thrust was greater than 1100 pounds. Valid comparisons of the noise levels of two propellers can only be made when they produce the same thrust. Hence, the second condition at which noise measurements were made, was when the propellers were producing the thrust produced by the four-bladed wooden propeller, 1100 pounds. The performance characteristics at maximum throttle and the noise levels at 1100 pounds thrust are discussed in the following section.

8 Bladed, 6'11" Propeller Inside Shroud

The performance of the eight-bladed propeller is shown in Figure 30. At the lower pitches, i.e. at 8° and 10°, the maximum rpm of 2650 was obtained at partial throttle. The thrust, power and figure of merit C_M, have maximum values at the 10° pitch setting. The corresponding thrust of 1500 pounds is the maximum obtained in all the tests. The figure of merit C_M is larger than that obtained with the 6'6" propeller. However, C_M is not as large as that predicted by the model tests. This probably results from the fact that the blade tips are very lightly loaded and under these conditions the shroud is not very effective in providing thrust. As the pitch of the blades is increased, the shroud should become more effective a conclusion which seems to be borne out by the rise in the value of C_M at 14° pitch.

Figure 31 shows the variation of sound pressure level around the airboat with the 8 bladed propeller operating at different pitches. At all the pitch settings, the rpm of the propeller was adjusted to obtain a thrust of 1100 pounds. It can be seen that the noise decreases with increasing pitch and is a minimum at the 14° pitch.

4 Bladed, 6'11" Propeller With Shroud

The performance of the four bladed propeller is shown in Figure 32. The maximum thrust of 1400 pounds is reached at the 12° and 14° pitches with figures of merit, C_M, about the same as those of the 8 bladed propeller. The noise levels around the

boat when the propeller is delivering 1100 pounds of thrust are indicated in Figure 33. It can be seen that the noise levels decrease with increasing pitch and are a minimum at the 14^{o} pitch. The noise levels at the 14^{o} pitch are the lowest of all the combinations of number of blades and pitches tested.

2 Bladed, 6'11" Propeller Inside Shroud

The performance of the 2 bladed propeller is shown in Figure 34. The rpm of the propeller was held constant at 2650, until the thrust produced reached 1300 pounds. It was calculated that distributing a larger load between two blades would stress them to an unsafe limit. This was, of course, a conservative limit since it was not known how much of the total thrust was being developed by the shroud. Thus, it was decided to make measurements at the 16^{o} and 18^{o} pitch settings with the rpm required to produce 1300 pounds of thrust. It was estimated that the engine power was sufficient to have turned the propeller at 2650 rpm for these two pitches. At this rotative speed, the thrust, power and C_M would have been correspondingly higher than the values shown. The C_M values obtained are high and in the range predicted by the model tests.

Despite the high values of C_M, the noise levels when producing 1100 pounds are not particularly low as indicated in Figure 35. The pitch produces the least noise.

Figure 36 compares the noise levels of the 2, 4, and 8 bladed propellers operating at their quietest pitch settings with the noise level of the 4 bladed wooden propeller. It can be seen that

the 4 bladed propeller at the 14° pitch is the quietest. There is a reduction of 2 db along the propeller axis, 12 db in the plane of the propeller and 8.5 db at $\theta = 135^{\circ}$. The four bladed propeller also appears to be properly matched to the 400 horsepower engine. This propeller delivers its maximum thrust of 1400 pounds when absorbing 390 horsepower at 2550 rpm. This power rating and rpm are close to the maximum ratings of the engine. Under these conditions, the engine manual indicates a fuel consumption of 29.5 gals/hr, with the mixture setting for the best power. During cruise conditions, a thrust level of 1100 pounds will presumably be demanded. The four bladed propeller will provide this thrust while absorbing 247 horsepower at 2250 rpm. Under these conditions, the engine manual indicates a fuel consumption of 17 gals/hr with the mixture setting for best economy. Thus, with the new four bladed propeller, it will be possible, with a given quantity of fuel to greatly increase the range obtained using the 4 bladed, unshrouded, wooden propeller.

WATER JET IMPELLER DESIGN

As mentioned in the introduction of this report, HYDRONAUTICS, Incorporated proposed to improve the performance of an existing water jet system by redesigning the pump impellers. A commercial water jet unit obtained by the Army was installed in a boat and static tests were conducted at dockside. These tests indicated that the static thrust increased as the square of the rpm at low values of the rpm. At higher rpm, cavitation began to affect the performance of the impellers and a peak static thrust of 750 lbs was obtained at 3400 rpm, while absorbing 80 horsepower.

Improvement in the performance of the impellers can be obtained by redesigning the impeller to delay cavitation thereby making it possible to operate at higher rpm and to obtain increased thrust, although this larger thrust may be obtained at a lower efficiency. It is assumed that the engine is capable of delivering the increased power. The new impellers should thus deliver a larger thrust even without any change in impeller dimensions.

The commercial unit has two rotating impellers divided by a stator. Each impeller has 4 blades, the two impellers being identical. Preliminary calculations indicated that better performance can be obtained if the second impeller operates immediately behind the first with the stator placed behind the second impeller. Further calculations revealed that the two impellers could be replaced by a single impeller without any loss in performance. The following sections will describe calculations evaluating the water jet performance, the design of a new impeller and stator and their construction and installation in the water jet unit.

CALCULATION OF MAXIMUM POWER ABSORPTION

In order to develop maximum thrust, the impeller must be designed to absorb maximum power, without cavitation or separation. The maximum power that could be absorbed by an impeller of the given size (7" diameter) was calculated in the following manner. Since the engine was rated at 160 horsepower and 4500 rpm, the impeller head and discharge necessary to absorb that power, were

calculated. It was then necessary to see if an axial-flow impeller could be designed to deliver that head and discharge at that rpm without cavitation or separation. If this proved impossible new calculations were made starting with a lower power level. This procedure was continued until a power level was reached for which an impeller could be designed to deliver the required head and discharge.

Two criteria were used to determine the feasibility of designing an impeller for a given set of conditions. The first condition required that cavitation not occur at the tips of the blades when operating under static conditions. The second condition required that the foil at the hub section not be loaded to such a degree that separation would occur. This systematic study indicated that an impeller with the following design conditions absorbed maximum power.

Power absorbed (η_{pump} = 75 percent) = 57 horsepower.

Forward velocity of boat = 20 fps.

Thrust at cruise speed = 455 pounds.

Thrust at zero speed = 685 pounds.

Total pump head = 60 feet.

Pump discharge = 5.88 cps = 2640 gpm.

Pump rpm = 2400.

Jet velocity = 60 fps.

Single impeller

Specific speed = 5700

Net positive suction head = NPSH = 30.6 ft. of water.

Suction specific speed = 9500

Number of vanes = 8

Hub to tip diameter ratio = 0.6

NACA 67 mean line and NACA 0 series, thickness distribution used for blade sections

Degree of reaction = 82 percent at tip and 50 percent at hub.

The impeller was designed at five cylindrical sections using the method outlined in Reference 7. A schematic drawing of one of the eight blades and several cylindrical sections of that blade are presented in Figure 37. Complete engineering drawings of the impeller and the guide vanes have been sent to the sponsor. The design method consists of defining an interference streamline and placing an airfoil section along this streamline to generate lift. The interference streamline at one blade section is obtained by replacing all the other blades by radial vortices and determining the interference of all the other blades at the blade section under consideration. The lift required at this blade section is developed entirely by camber at zero angle of attack.

The pressure distribution along the impeller sections was calculated to determine if the pressure at any point dropped below vapor pressure with resulting cavitation. The pressure distribution along an airfoil as determined from thin wing theory or as obtained from a wind tunnel test is modified when placed in a pump due to the fact that the average pressure rises from the inlet to the exit of the pump. The average pressure along the foil

could change from two causes. The first is due to the change in axial velocity from changes in hub diameter or from changes in the thickness of the foil. The second is due to changes in the swirl velocity due to the action of the blades. The average pressure rise and the pressure along the upper and lower surfaces of the impeller sections were obtained from a computer program written for this purpose. Figure 38 shows these pressures in feet of water along the chord length of the section. It can be seen that the pressures remain well above the vapor pressure of water and hence the pump is expected to operate cavitation free at the design condition.

Another computation was made to determine the pressure distribution at off-design operation; for example, when the operating conditions are such that the impeller blade has a 2 degree angle of attack. The pressure distribution for such a case is shown in Figure 39. It can be seen that the pressures along the upper leading edge fall below the vapor pressure and leading edge cavitation will occur over about 9 percent of the chord length. It is, however, expected that the actual operating condition will not differ so markedly from the design condition and hence the pump will not cavitate.

The cavitation studies described in the previous paragraphs apply to the critical tip region. At the hub radius, another problem is likely to be the controlling factor in the design; this problem is one of boundary-layer separation along the foil. Separation of the flow along a foil can occur if the foil has too large a camber or angle of attack or if the foil operates in a

positive pressure gradient. In the case of a pump design, the foil operates in a positive pressure gradient because of the head rise occurring as the flow passes through the blade row and hence the maximum lift coefficient in such a case will be less than the maximum lift coefficient obtained by the same foil in a wind tunnel test. This decrease in maximum lift is, of course, dependent on the magnitude of the head rise through the impeller. The maximum lift coefficient of the foil can be determined from wind-tunnel tests and, from these data, it is possible to predict, with engineering accuracy, the maximum lift coefficient that can be safely used in design for the given pressure gradient. The actual lift coefficient used in design is kept below this estimated maximum to be sure of separation-free flow. Details of this method of obtaining the maximum lift coefficient of a foil in a positive pressure gradient are given in Reference 8.

To help reduce the operating lift coefficient at the hub, the mean relative velocity past the foil should be increased. This can be done by increasing the hub radius. The existing impellers have a hub to tip diameter ratio of 0.4. In the new single impeller, the hub ratio is increased parabolically from 0.4 to 0.6 in a short distance and then remains constant at 0.6. Because of the change in hub diameter ratio, the pitch angle of the blade in that region has to be decreased by about 6 degrees. Hence all the cylindrical sections are shaped as shown in Figure 37.

A stress analysis was conducted to determine the bending stress that occurs at the hub. Because the radial extent of the blade is small, the bending moment due to the hydrodynamic forces

is small and because of the large camber of the hub section, the section modulus is large. Hence, the maximum stress at the root section is considerably less than the allowable working stress selected (10,000 psi).

DESIGN OF GUIDE VANES

The degree of reaction of the impeller varies from 82 percent at the tip radius to 50 percent at the hub. If the hydraulic efficiency of the impeller is to be raised from these values to about 95 percent, a set of guide vanes must be installed to convert the rotational kinetic energy of the flow to pressure energy. The flow behind the stator will then be nearly axial in direction. The existing water jet unit has a splitter plate behind the second impeller which was bent to act as a guide vane. This bent splitter plate has been milled out so as to then be aligned with the axial flow leaving the stator. This removal of the existing curved lips on the splitter plate will also provide more space for the new guide vanes.

The design of the guide vanes is slightly different from the design of the impeller. The hub of the guide vanes decreases from a radius of 2.1 inches to a radius of 0.8 inches. Thus, the flow will take place along conical surfaces and the foil sections are designed along these surfaces. Taking this conical flow into consideration a stator was designed using the methods described in Reference 8. A drawing of the guide vanes or stator is shown in Figure 40.

CONSTRUCTION AND INSTALLATION

The construction of the eight bladed impeller was a difficult task and some design features had to be compromised to facilitate construction. Thus, it was decided to replace the NACA 0 series thickness distribution with a section of uniform thickness, with the leading edge rounded and the trailing edge properly tapered. This change is not likely to cause major changes in the pressure distribution since the camber was more important than the foil thickness in determining the pressure distribution. Thicker sections were also desirable since the blades were to be welded to the hub. The heat of welding would have warped the thin sections. The eight blades were made individually from stainless steel and then they were welded to the hub. The blades were then properly finished and the tips of the blades turned down to its correct diameter. The same procedure was used for the fabrication of the guide vanes. Photographs of the impeller and stator are shown in Figures 41 and 42.

Installation of the impeller and stator in the existing water jet was accomplished by making a few minor modifications to the unit. Thus the original shaft was replaced by another to accept one large impeller instead of two small impellers. The hub of the guide vanes was used to house a bushing for the shaft. Part of the hub and the two splitter plates of the existing unit had to be milled out to accommodate the new guide vanes. Four, lock-bolts were used to clamp the two sections of the water jet unit together. Details of the final assembly of the water jet unit are presented in Figure 43.

CONCLUSIONS AND RECOMMENDATIONS

The noise radiated by the airboat consists mainly of propeller noise. This noise can be reduced by proper design of the propeller and the use of an effective shroud. In the design of a quiet propeller, a large number of blades is desirable if the blade area ratio (BAR) does not increase excessively. A high BAR increases the wake-induced and the vortex noise, thereby nullifying the reductions in rotational noise levels obtained by a large number of blades. In the design of a satisfactory shroud, it is imperative that the flow about the shroud not separate from the inner surface. The overall noise levels of a propeller decrease with the use of a good shroud but increase when separation occurs along the inside surface of the shroud. Two important features help to prevent separation in a shroud beside its own geometry. First, the clearance between the tips of the blades and the inside of the shroud should be a minimum. Second, lightly loaded propeller tips are likely to cause separation and hence the shroud performance increases when tips are heavily loaded. Thrust fluctuation noises can be reduced by providing uniform inflow into the propeller.

For the commercial propeller blade chosen and for the designed shroud, a series of noise and thrust measurements were conducted, changing the number of blades and the blade pitch. These tests showed that a four bladed propeller 6'11" in diameter at 14° pitch radiated the least noise when delivering 1100 pounds of thrust. The maximum thrust produced by this propeller is 1400 pounds and this thrust is delivered at close to the maximum power and rpm rating of the engine. Under this condition, the fuel consumption

is 29.5 gals/hr. This propeller delivers 1100 pounds of thrust when the engine is operating under economy cruise conditions. Under these conditions, the fuel consumption is only 17 gals/hr and hence for a given volume of fuel, the boat would have much longer endurance than with the original propeller. The noise reductions obtained with this propeller over the four bladed wooden propeller, while delivering 1100 pounds of thrust are 12 db in the plane of the propeller and 2 db along the propeller axis.

Studies of a twin engine airboat revealed that such a craft can be designed for the same static thrust and have 6-8 db lower rotational noise than the single engined airboat. Such a craft would use two engines of 180 horsepower and 4.5 foot diameter unshrouded propellers.

A new impeller and stator have been designed to replace two impellers and a stator in a commercial water jet unit. This new impeller has been designed to absorb a maximum power of 57 horsepower without cavitation or separation occurring in the impeller. Under these conditions, it should provide a thrust of 685 pounds under static conditions and will propel the boat at a speed of 20 fps when the total displacement of the boat is 4000 pounds. The impeller and stator have been fabricated and have been installed in the commercial water jet with a few minor modifications. The complete water jet unit is now ready to be tested.

REFERENCES

1. Gutin, L., "On The Sound Field of a Rotating Propeller," NACA TM 1195, 1948.

2. Trillo, R. L., "An Empirical Study of Hovercraft Propeller Noise," Hovering Craft and Hydrofoil, Vol. 5, Nos. 3 and 4, December-January 1965-66.

3. Yudin, E. Y., "On the Vortex Sound from Rotating Rods," NACA TM 1136, March 1947.

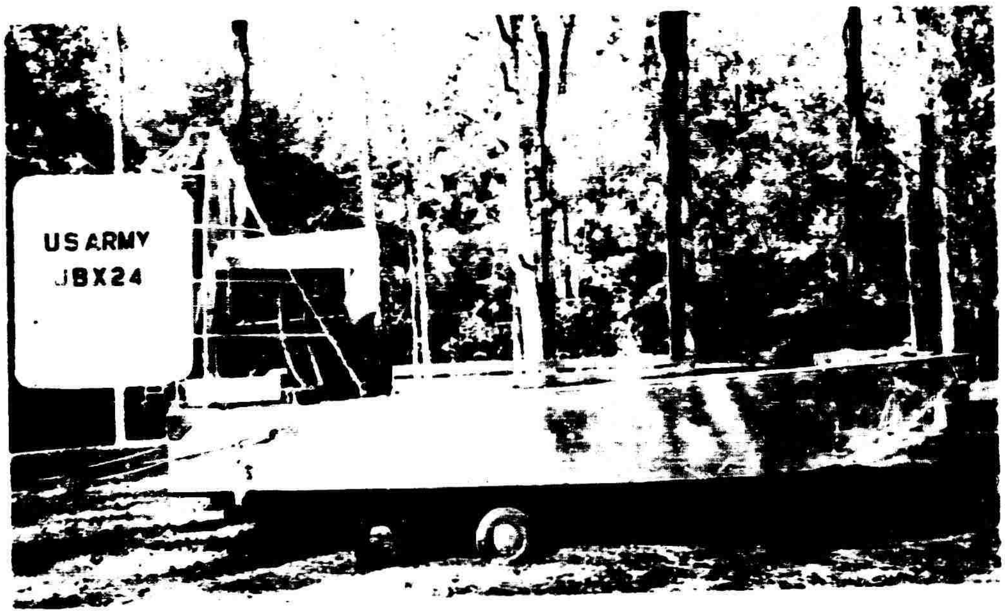
4. Hubbard, H. H., "Sound Measurements for Five Shrouded Propellers at Static Conditions," NACA TN 2024, April 1950.

5. Chen, C. F., "Feasibility Study of Supercavitating Propellers in Kort Nozzles - Phase I," HYDRONAUTICS, Incorporated Technical Report 005-1, December 1960.

6. "Testing of a Nozzle-Propeller System on the U. S. Army Airboat," HYDRONAUTICS, Incorporated Progress Report 532-6, September 1966.

7. Bowerman, R. D., "The Design of Axial Flow Pumps," Trans. ASME, pg 1723, November 1956.

8. Wislicenus, G. F., "Fluid Mechanics of Turbomachinery," Dover Publications, New York, N. Y., 1965.



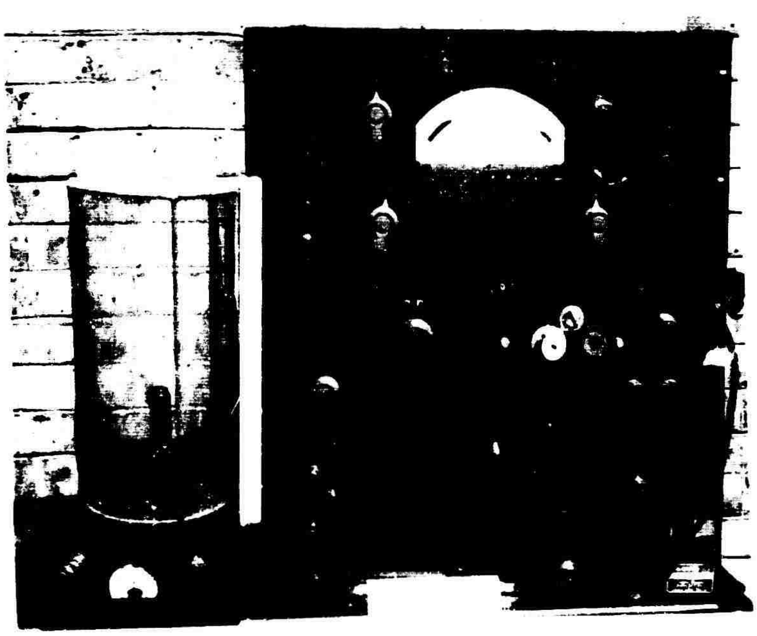


FIGURE 1 - AIRBOAT ON TRAILER AND INSTRUMENTS USED FOR NOISE MEASUREMENT TEST

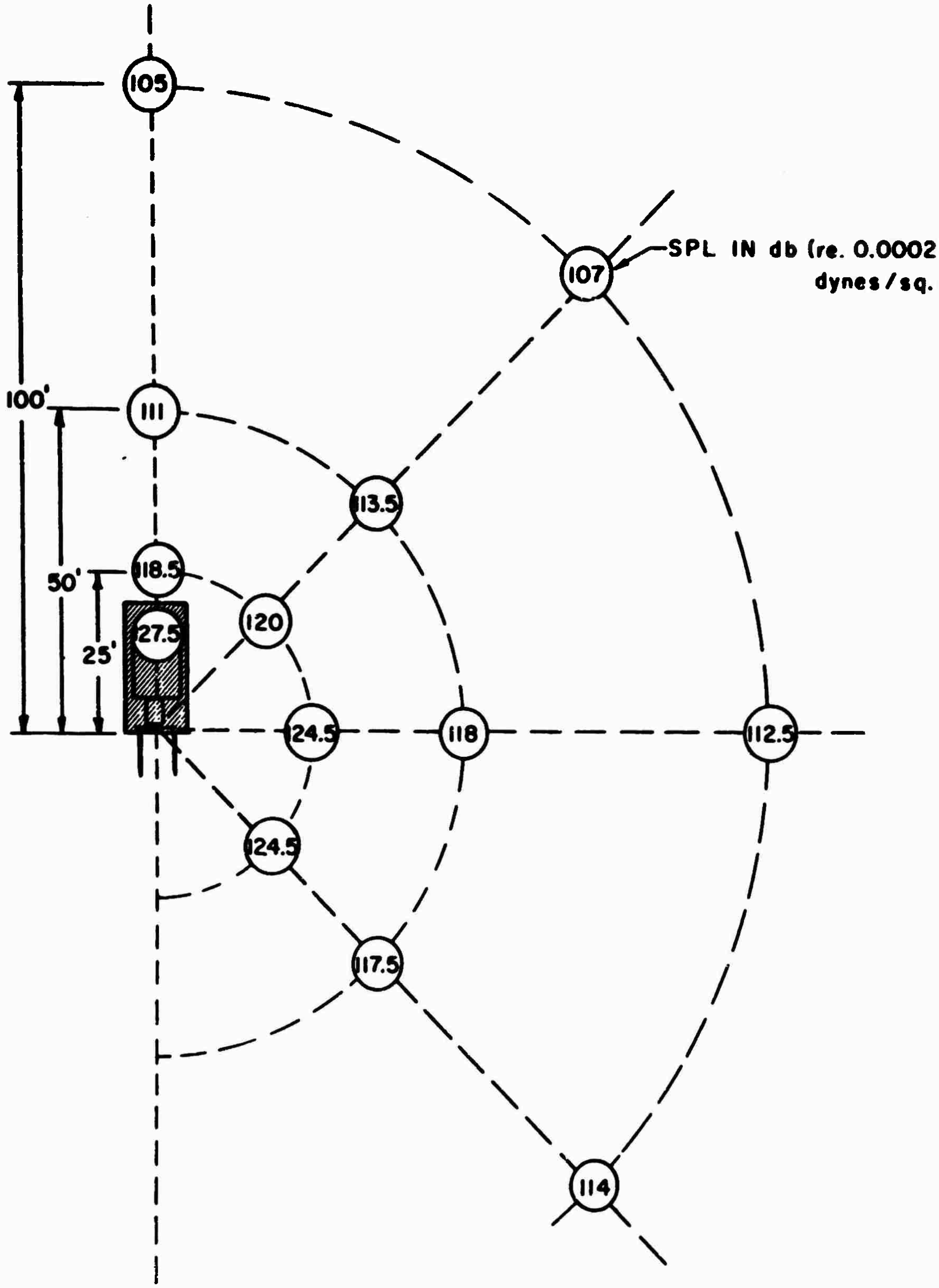


FIGURE 2 - OVERALL NOISE LEVELS AROUND AIRBOAT
AT START OF PROJECT N = 2600 RPM

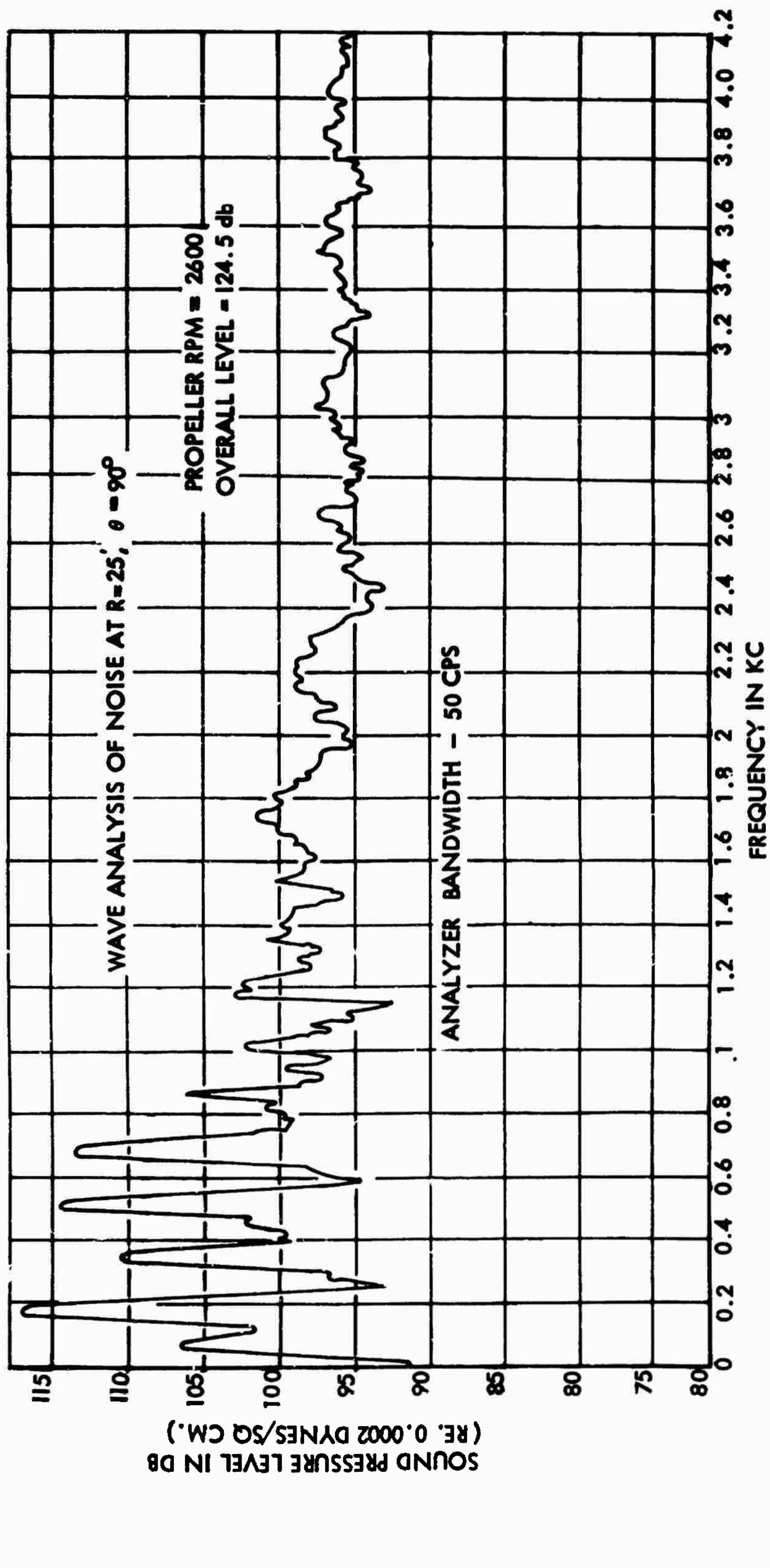


FIGURE 3 - TYPICAL RECORDING OF WAVE ANALYZER, PROPELLER RPM=2600

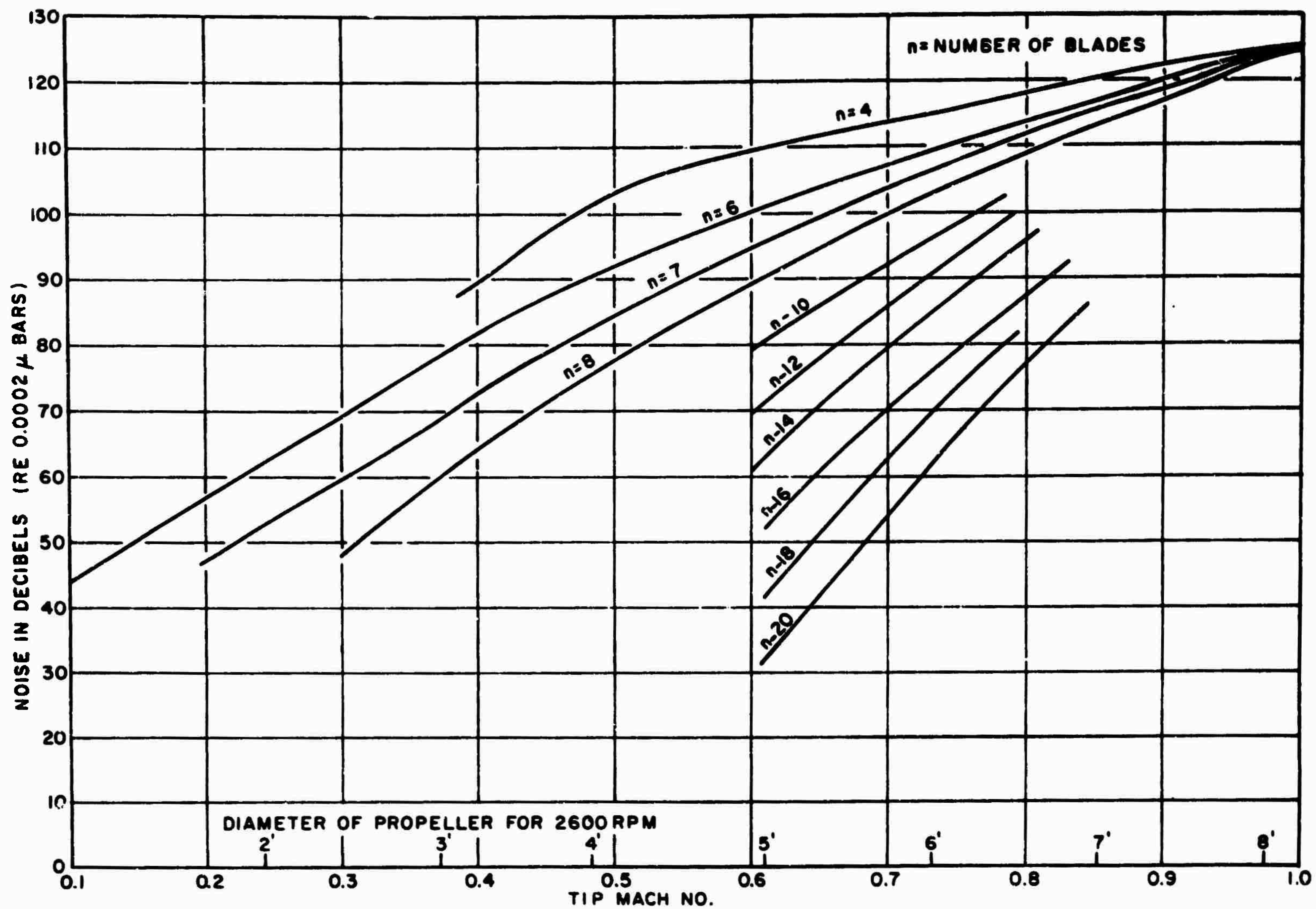


FIGURE 4 - SOUND PRESSURE LEVEL AS A FUNCTION OF TIP MACH NUMBER AND NUMBER OF BLADES

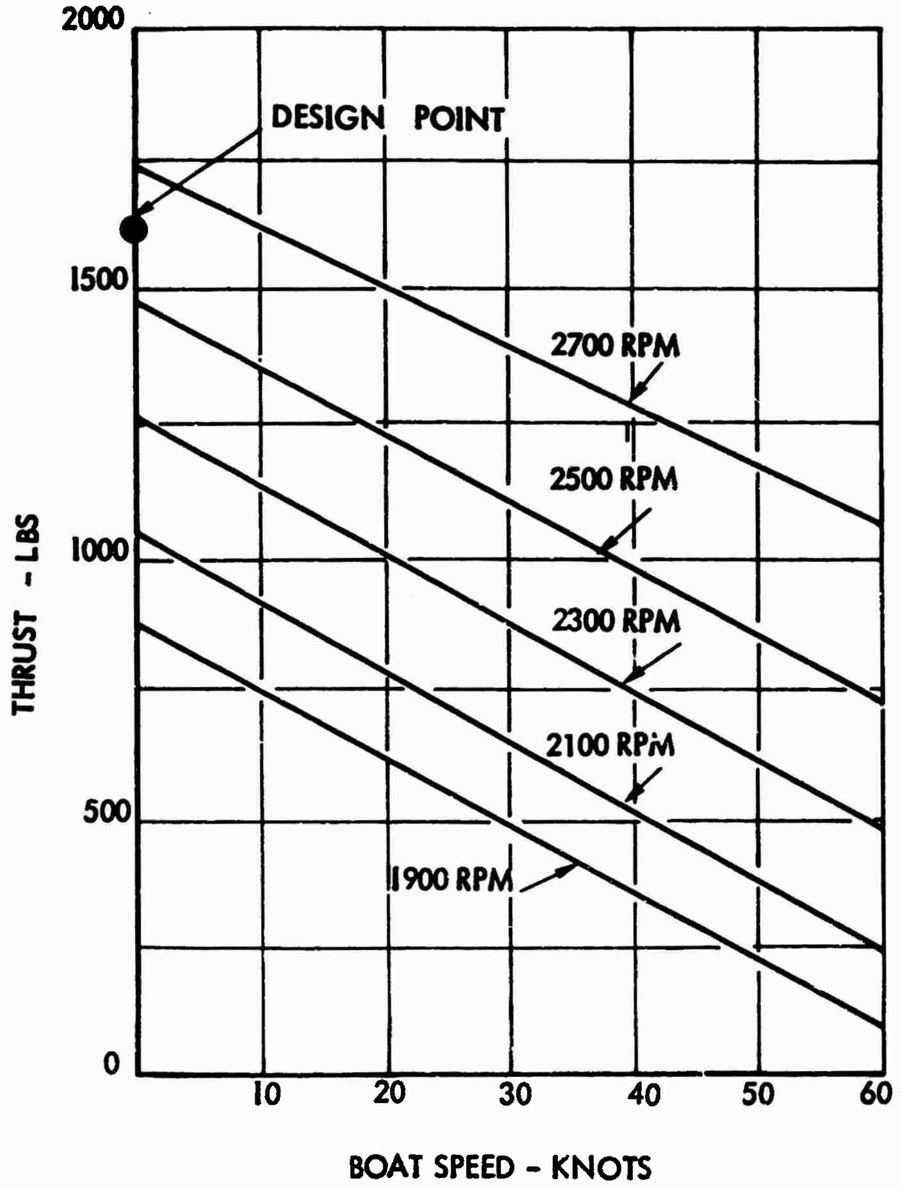


FIGURE 5 - VARIATION OF TOTAL THRUST WITH SPEED OF HYDRONAUTICS, INC. DESIGNED PROPELLER

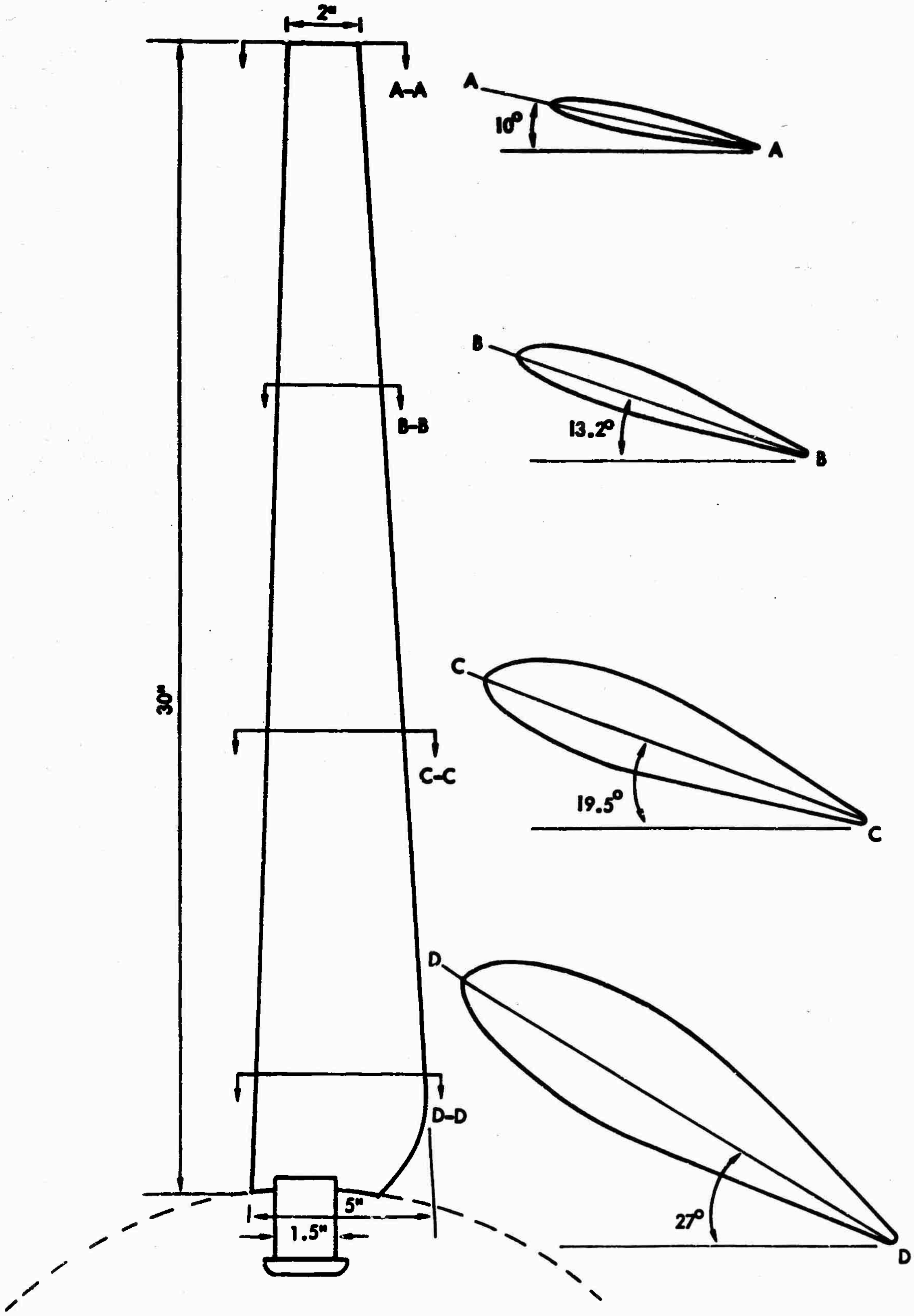


FIGURE 6 - HYDRONAUTICS, INC. PROPELLER BLADE DESIGN

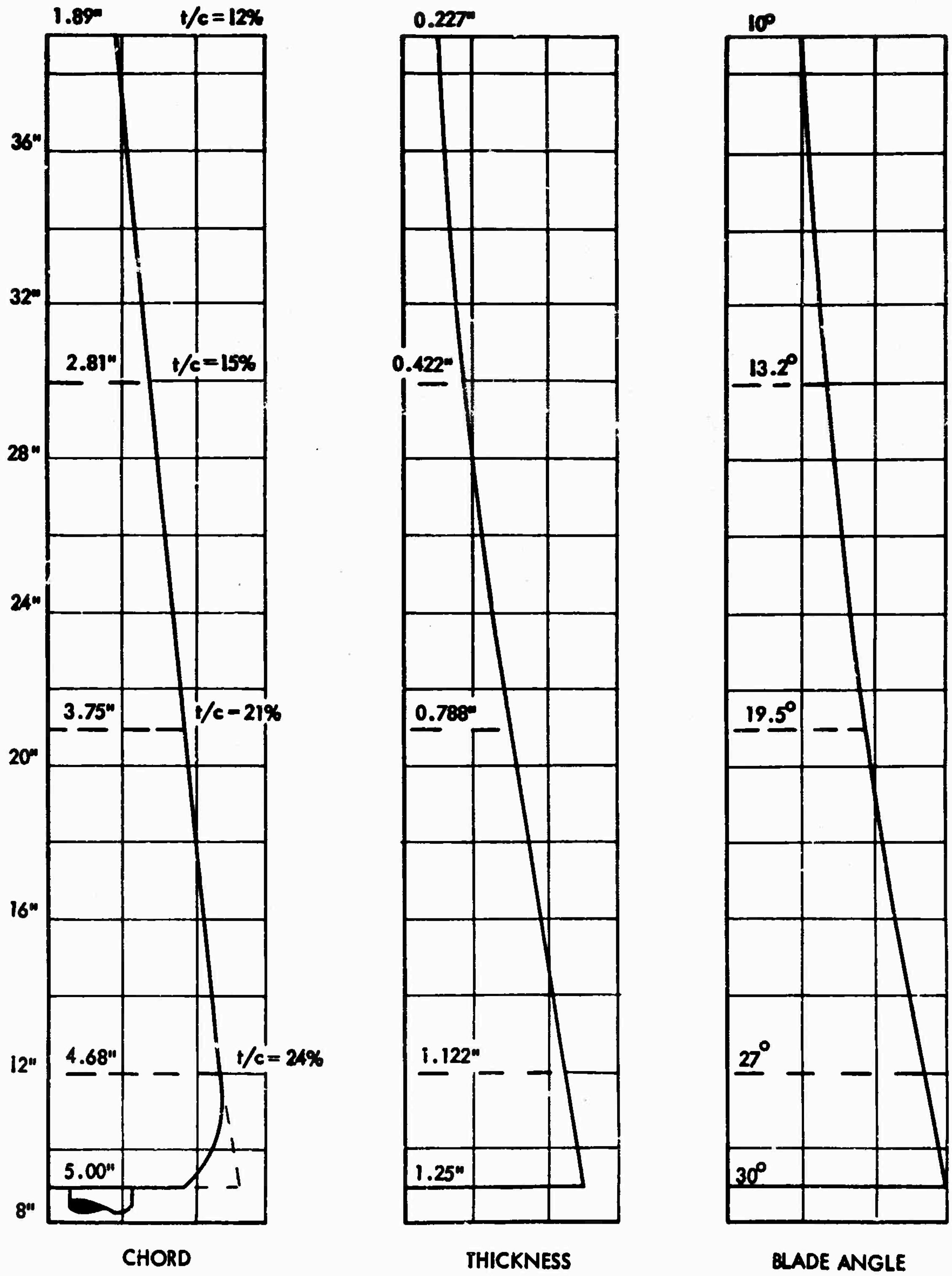


FIGURE 7 - CHORD, THICKNESS, AND BLADE ANGLE OF HYDRONAUTICS, INC. DESIGNED PROPELLER BLADE

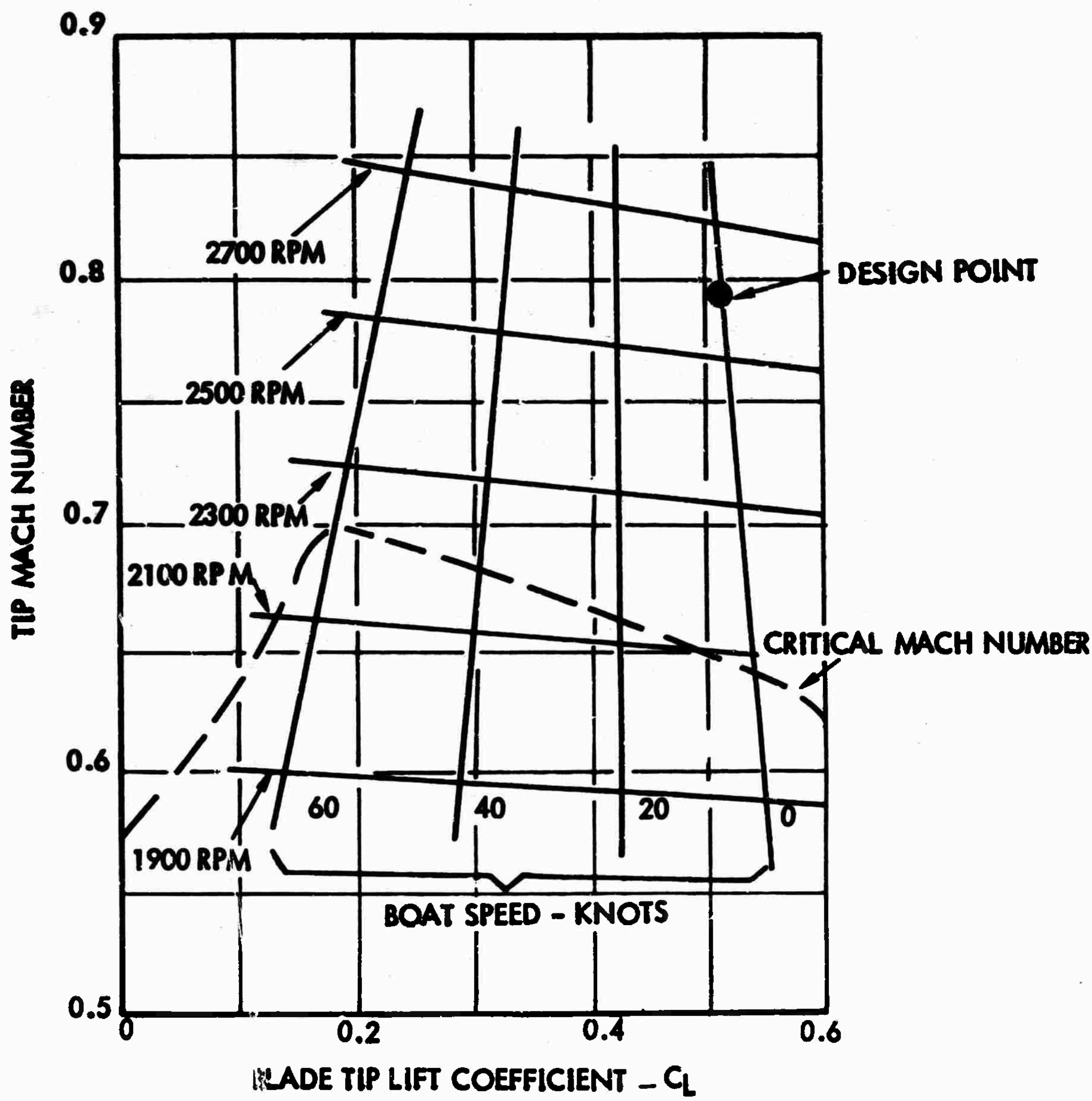
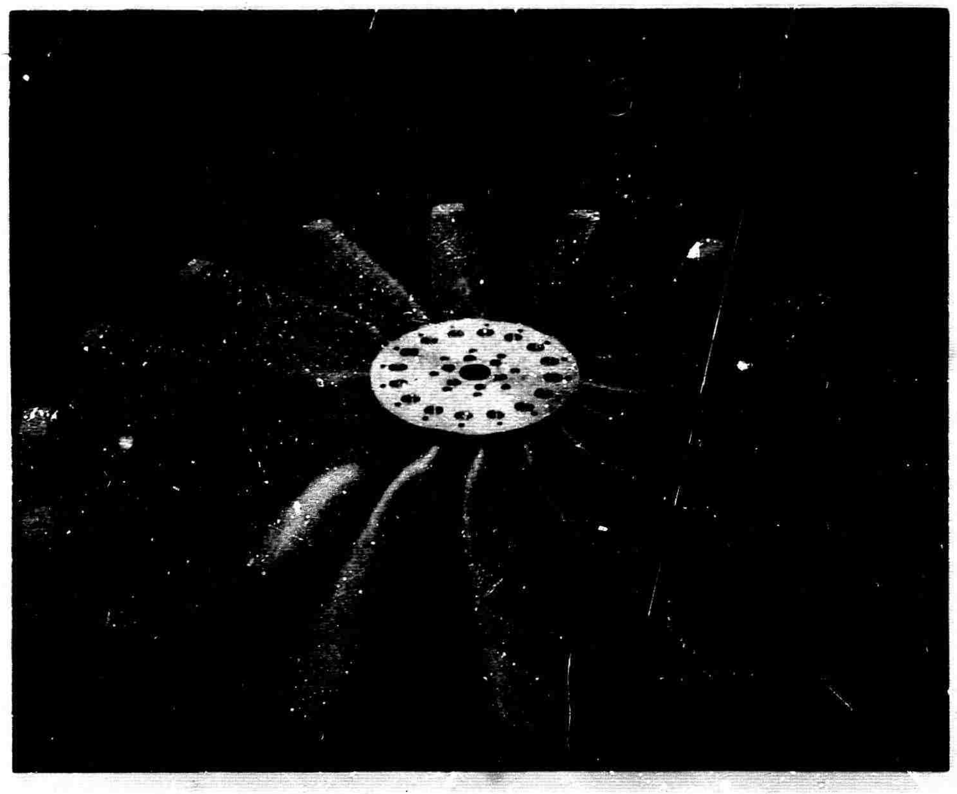


FIGURE 8 - RELATION BETWEEN CRITICAL MACH NUMBER AND TIP MACH NUMBER OVER THE RANGE OF OPERATING LIFT COEFFICIENTS



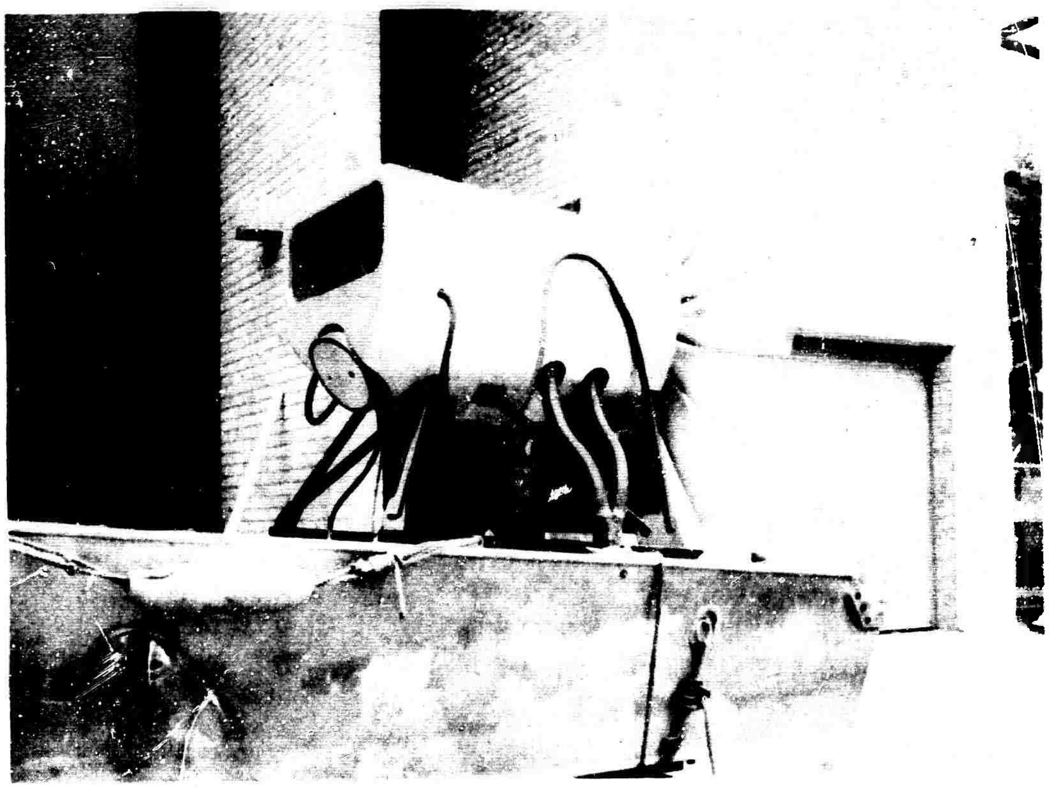
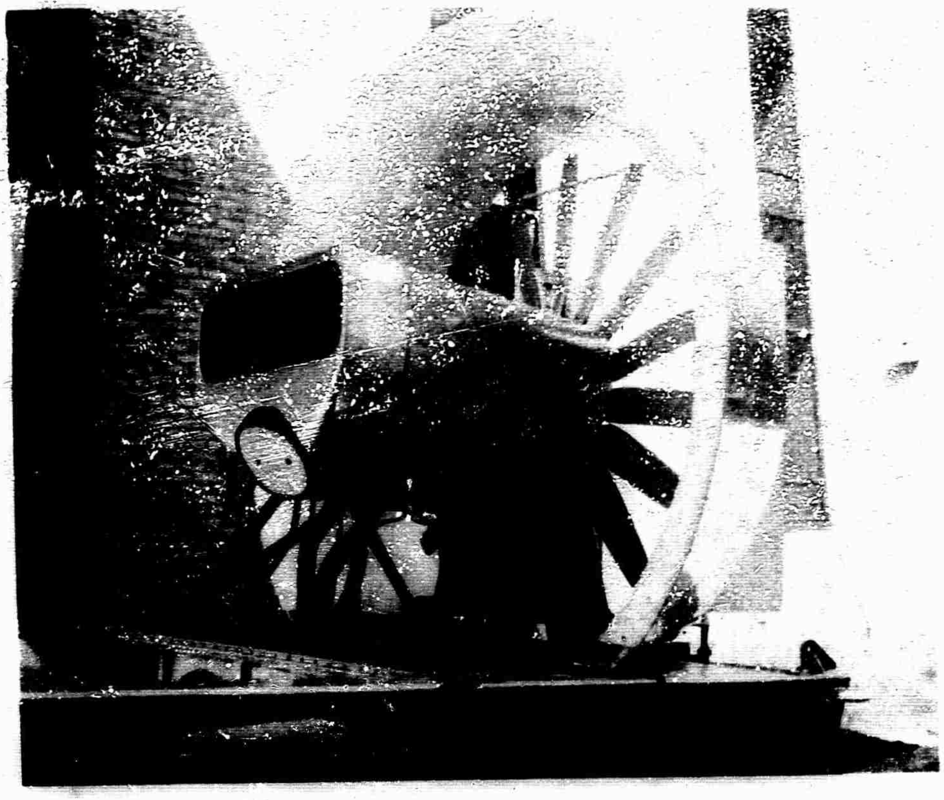


FIGURE 9 - SIXTEEN BLADED PROPELLER



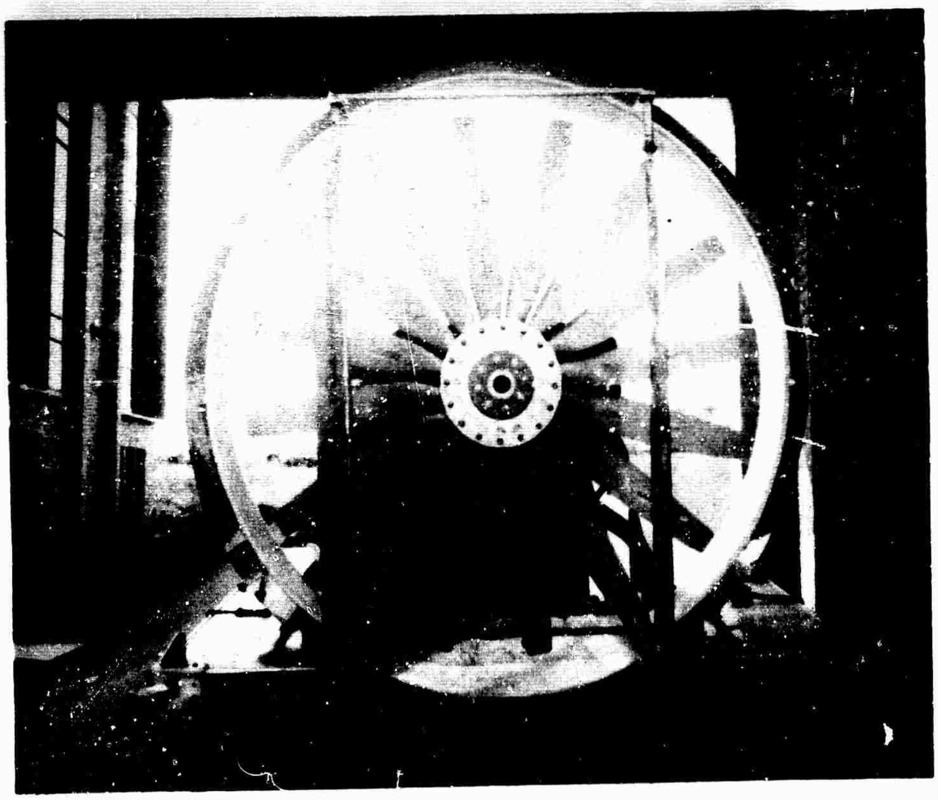


FIGURE 10 - SIXTEEN BLADED PROPELLER WITH SHROUD INSTALLED

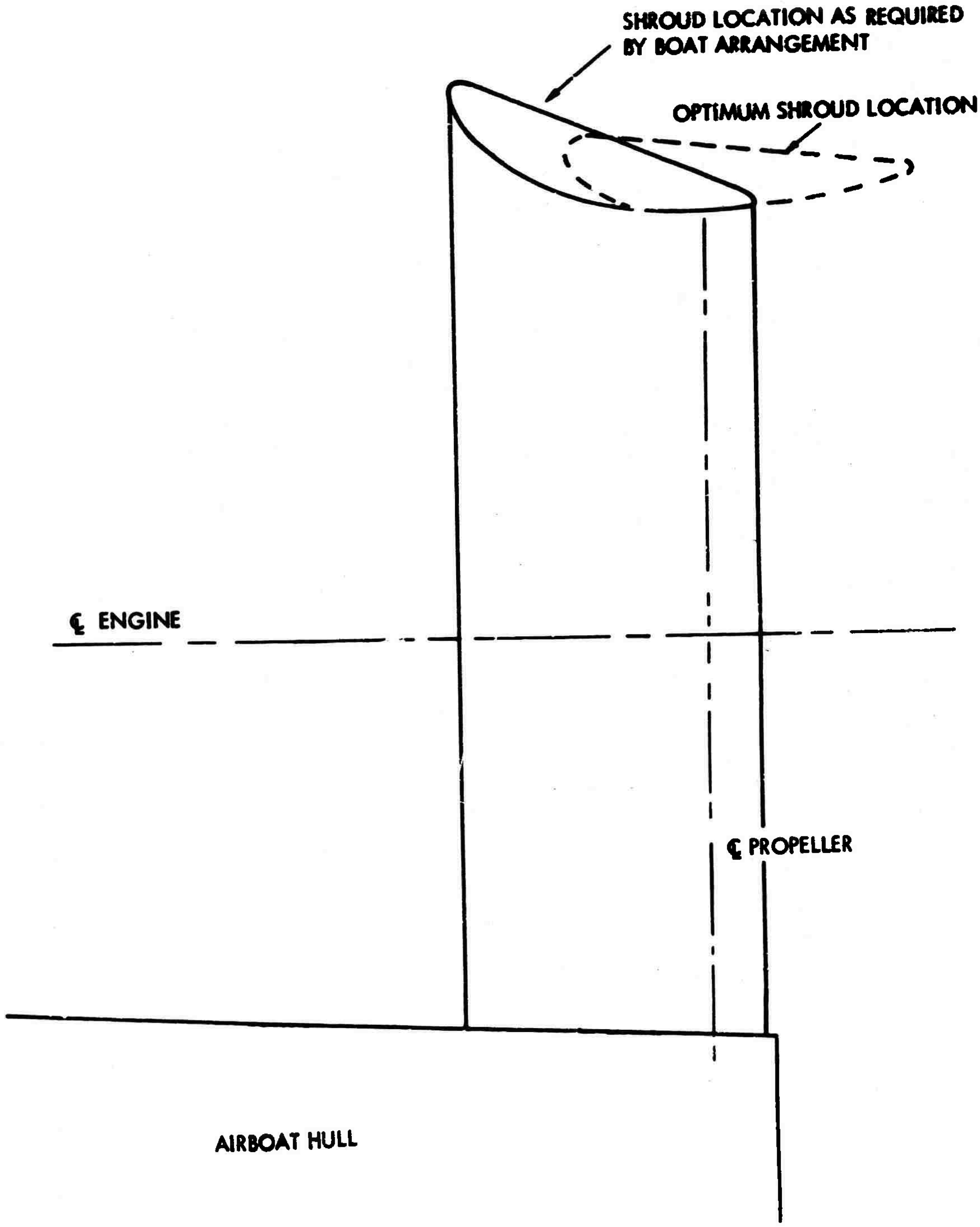


FIGURE 11 - SHROUD LOCATIONS ON AIRBOAT HULL

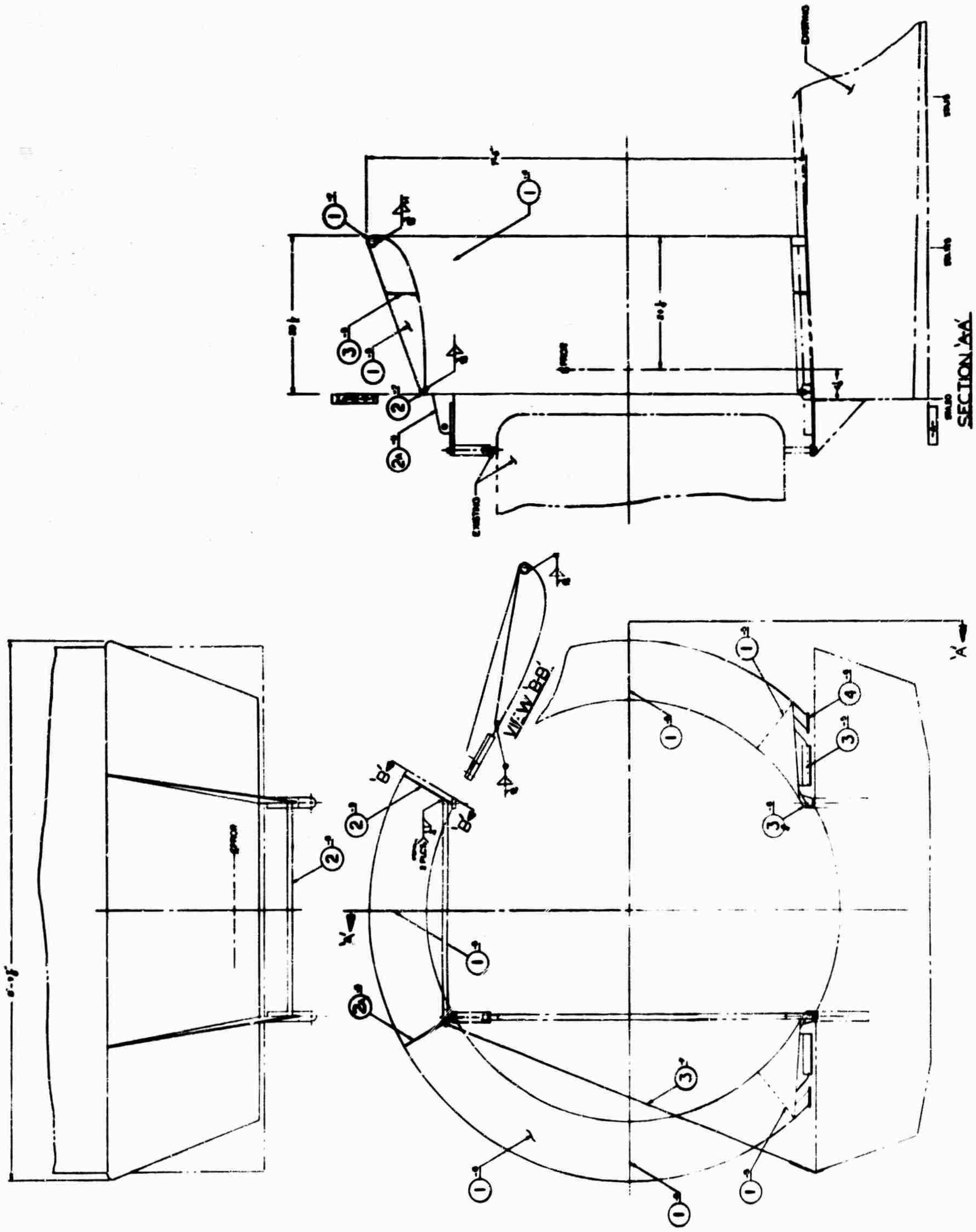


FIGURE 12 - SHROUD ARRANGEMENT ON AIRBOAT HULL

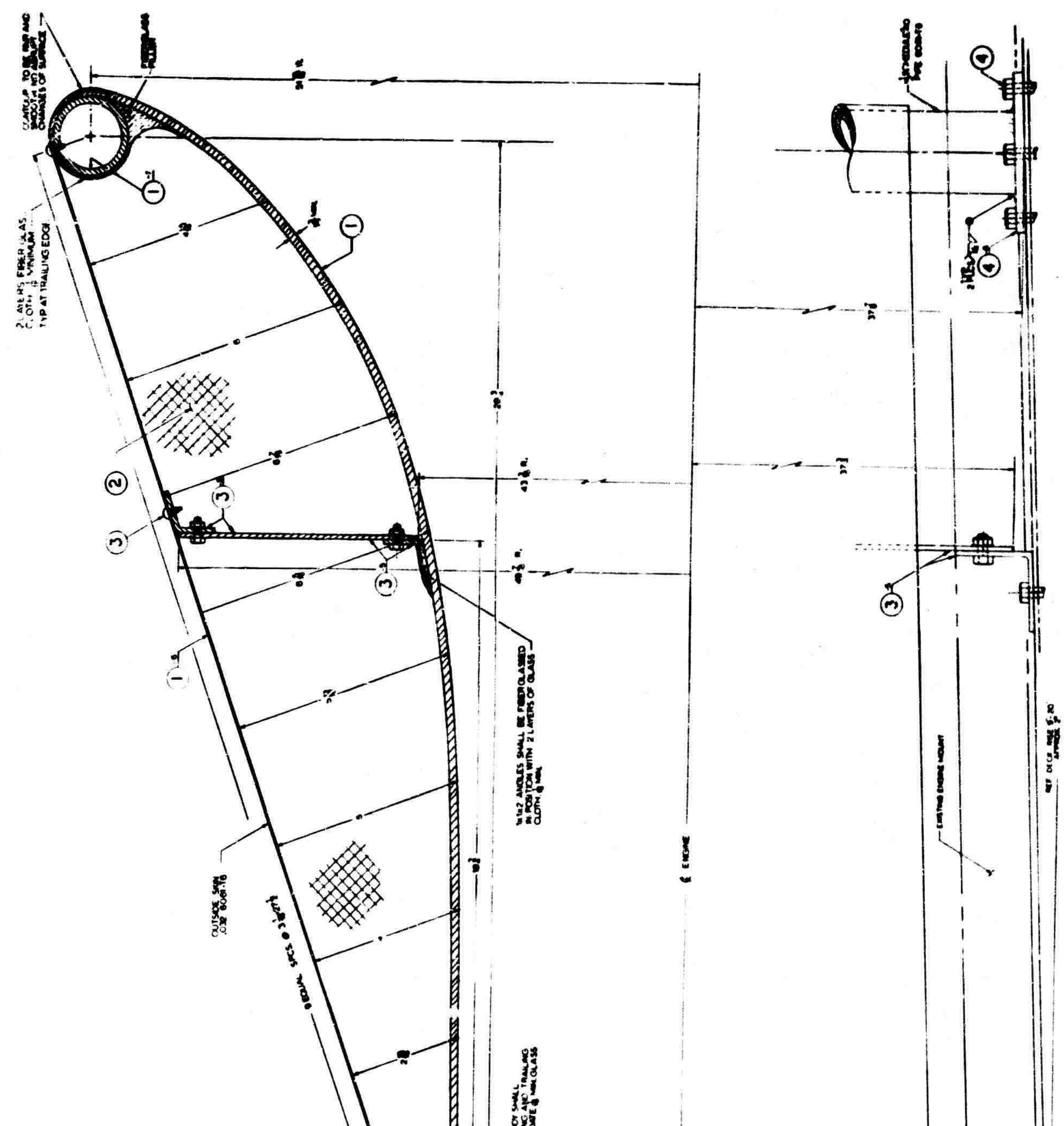


FIGURE 13 - SHROUD STRUCTURAL ARRANGEMENTS

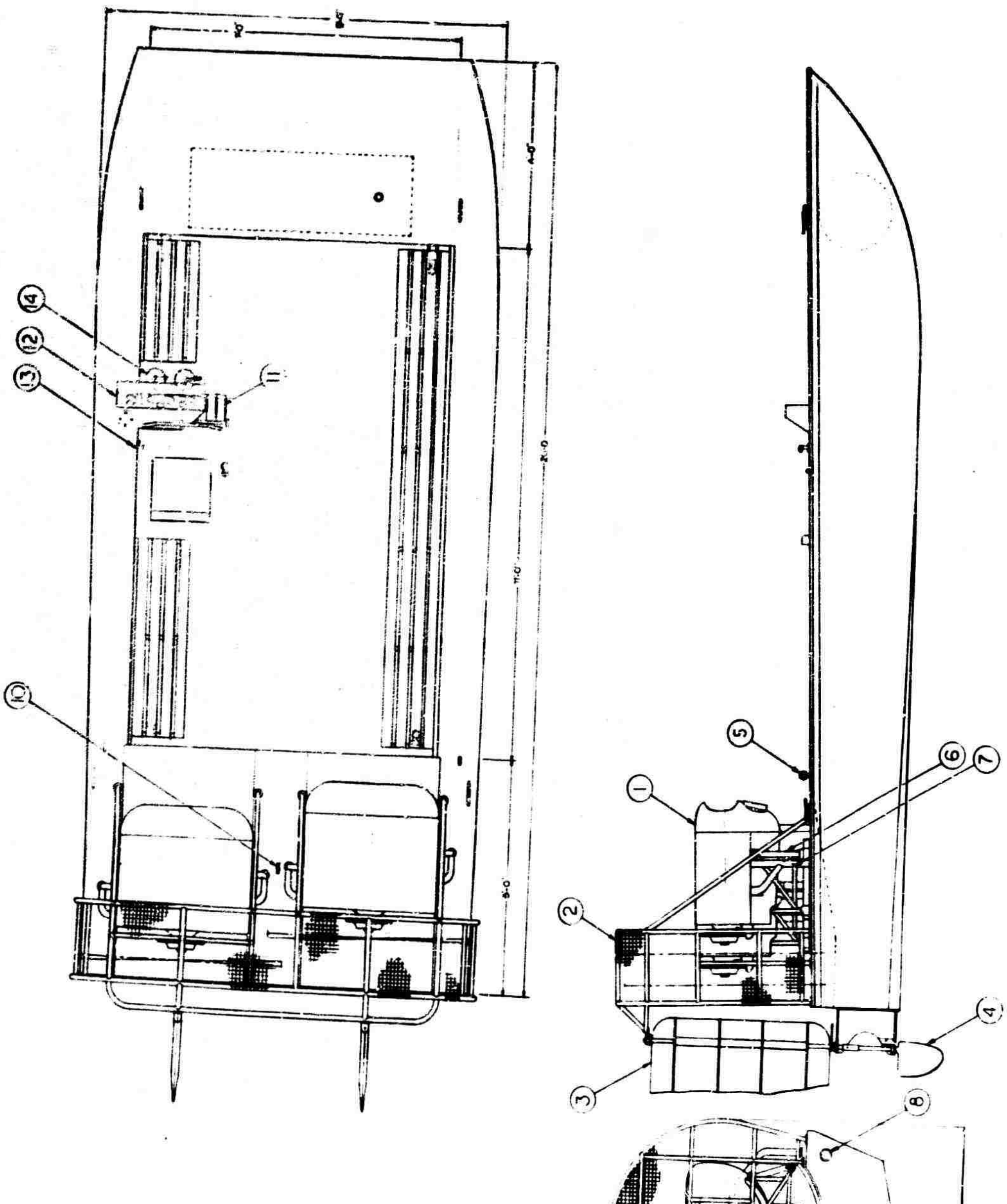


FIGURE 14 - TWIN ENGINE AIRBOAT ARRANGEMENT DRAWING

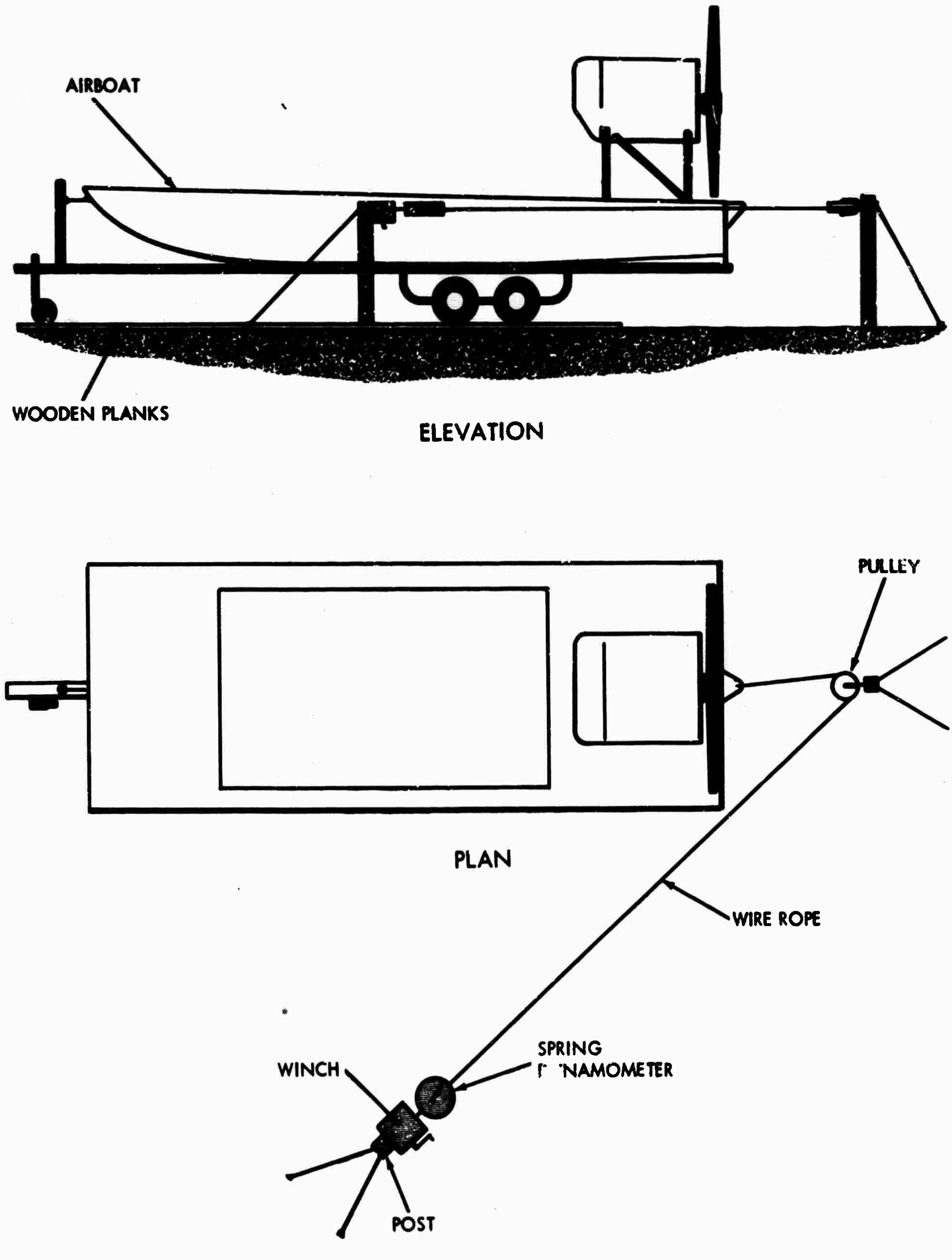


FIGURE 15 - TEST SET-UP FOR THRUST MEASUREMENTS OF AIRBOAT

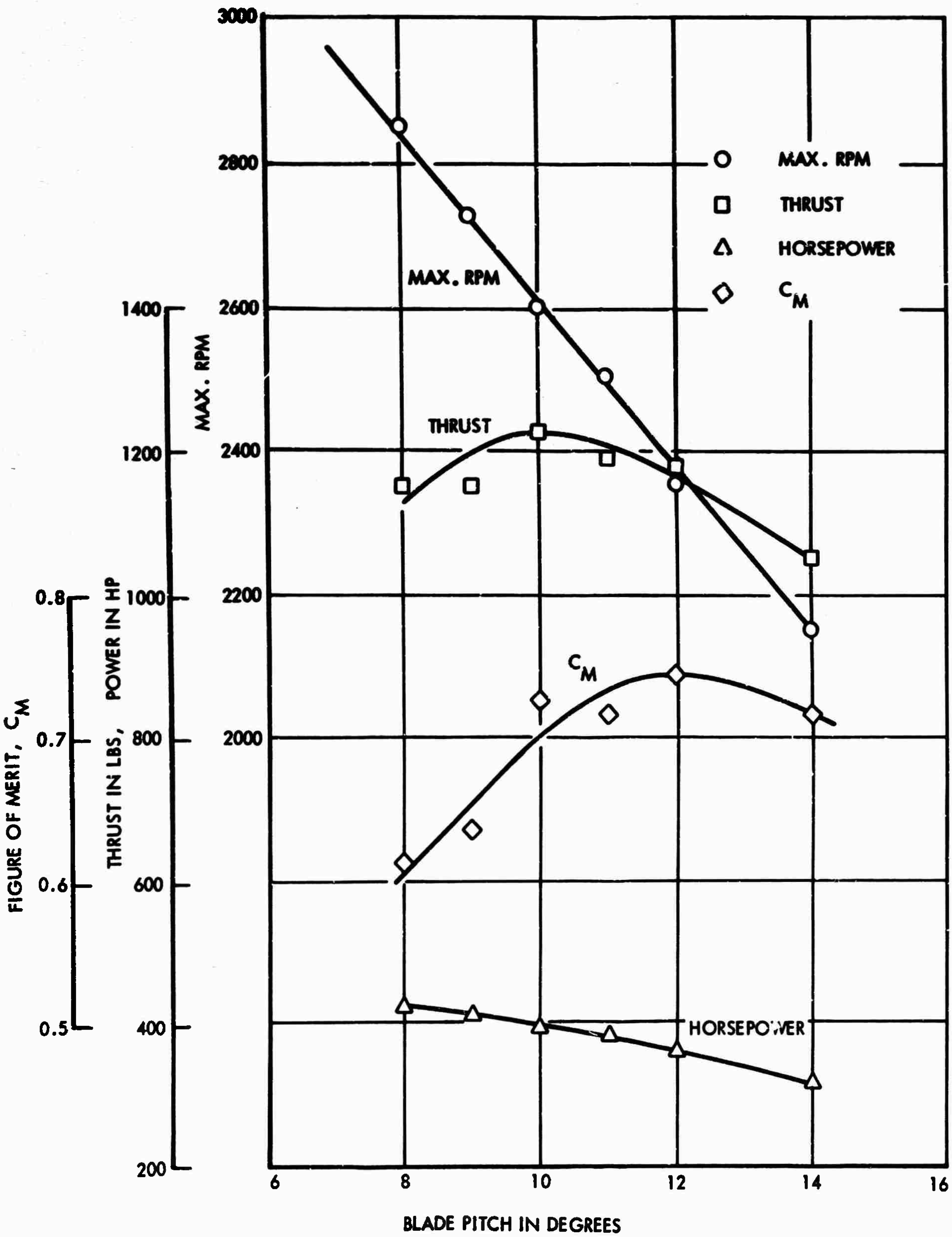


FIGURE 16 - PERFORMANCE CHARACTERISTICS OF 8 BLADED PROPELLER

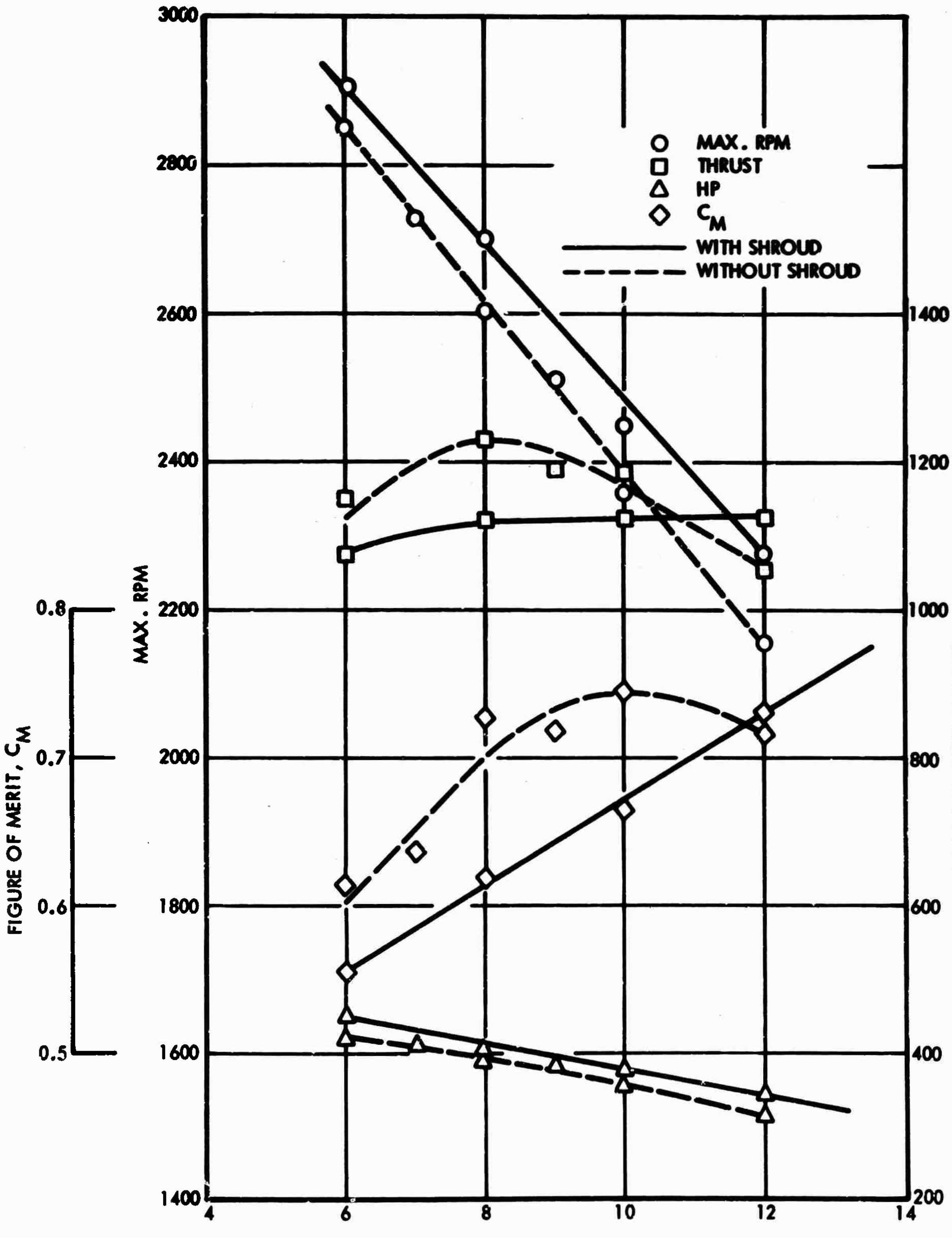


FIGURE 17 - PERFORMANCE CHARACTERISTICS OF 8 BLADED PROPELLER WITH AND WITHOUT SHROUD

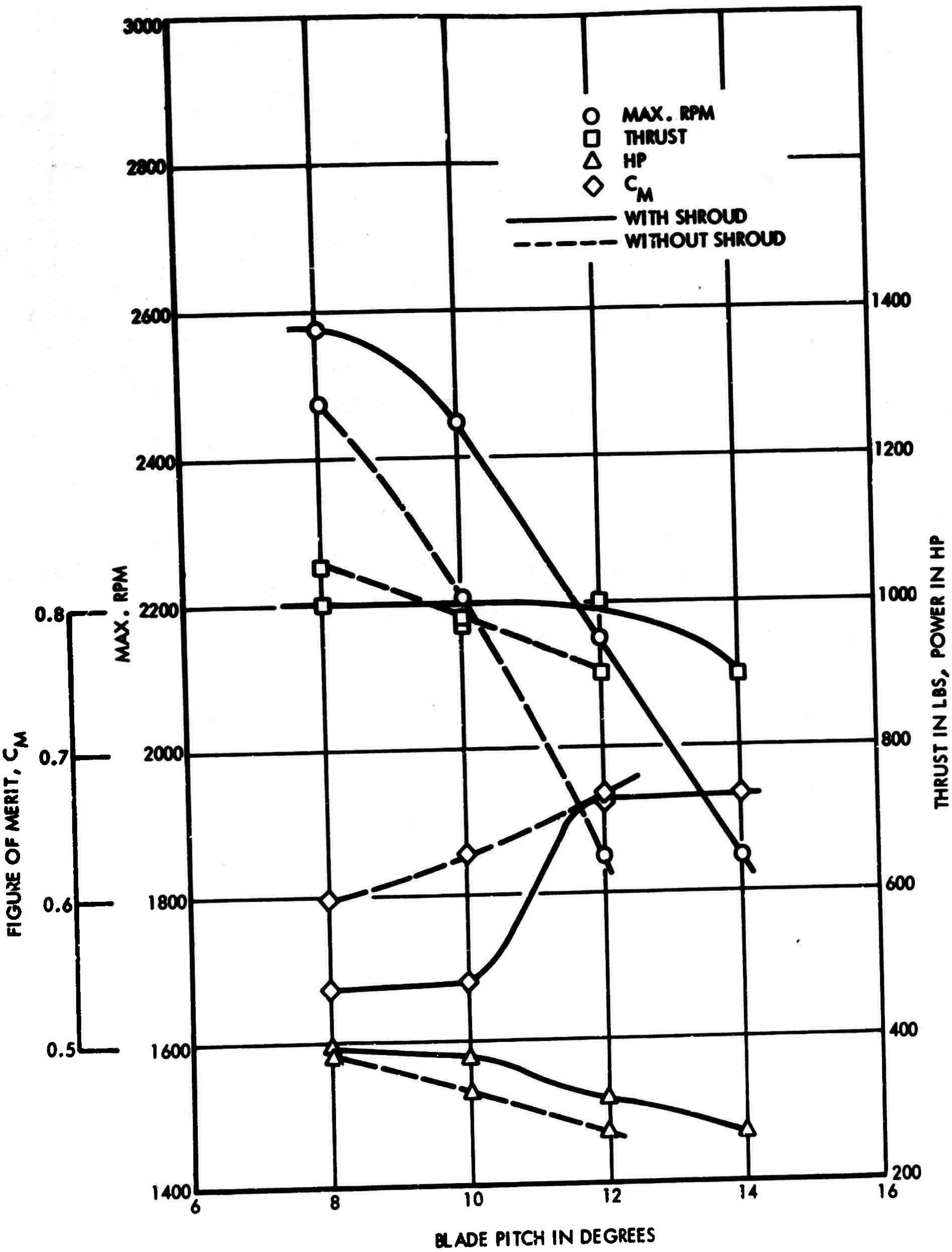


FIGURE 18 - PERFORMANCE CHARACTERISTICS OF 16 BLADED PROPELLER WITH AND WITHOUT SHROUD

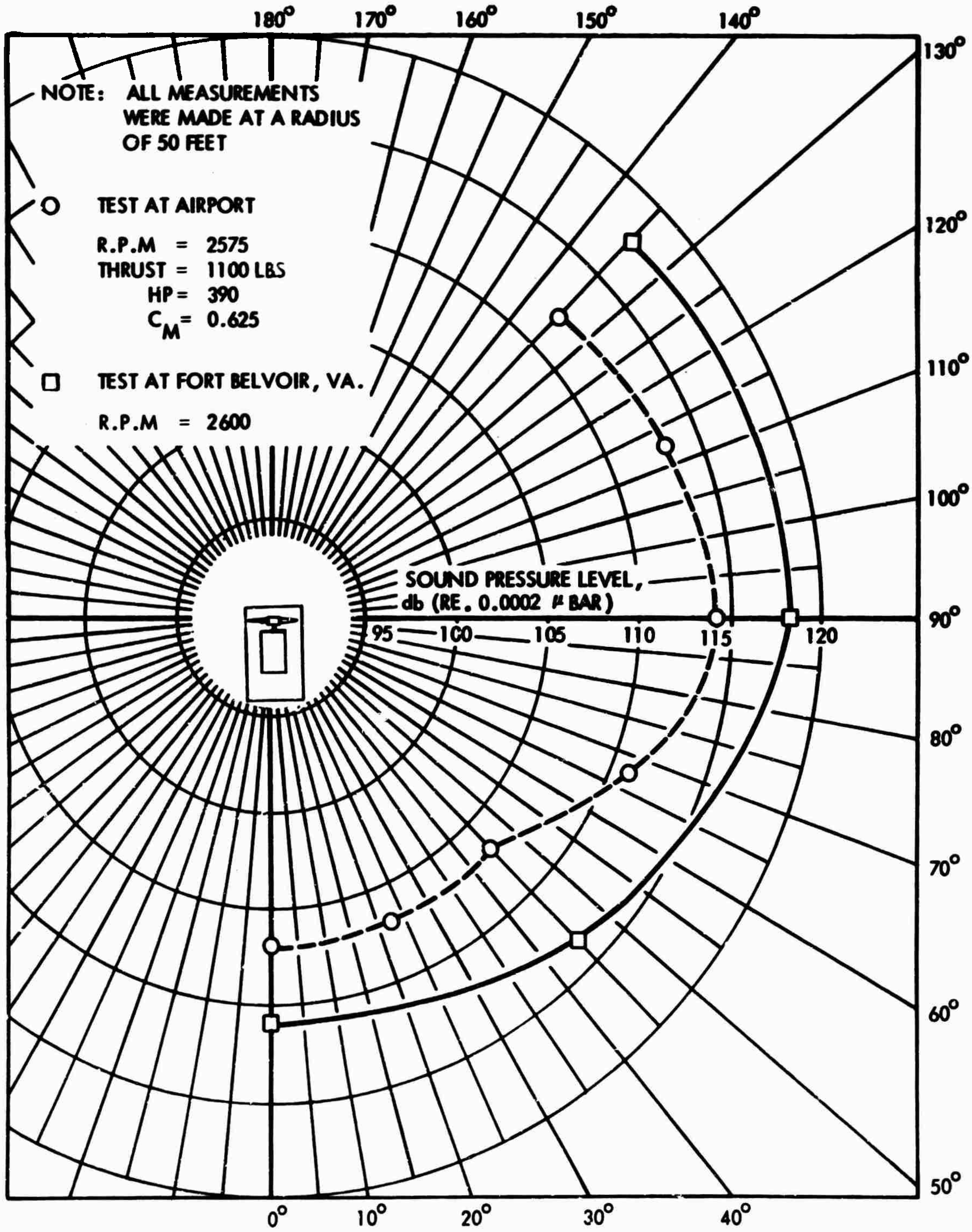


FIGURE 19 - SOUND PRESSURE LEVELS AROUND AIRBOAT WITH 4 BLADED WOODEN PROPELLER

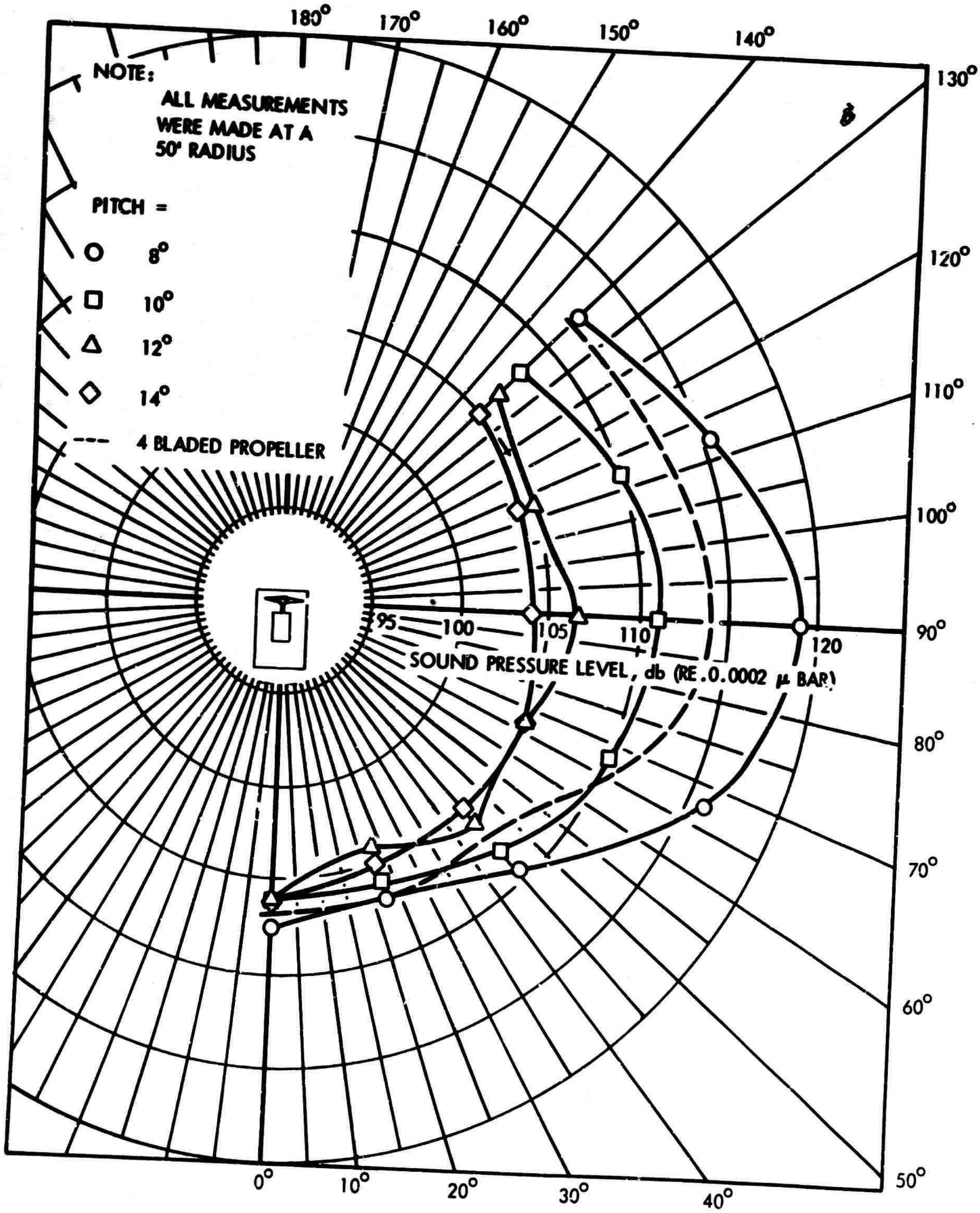


FIGURE 20 - SOUND PRESSURE LEVELS AROUND AIRBOAT WITH 8 BLADED PROPELLER

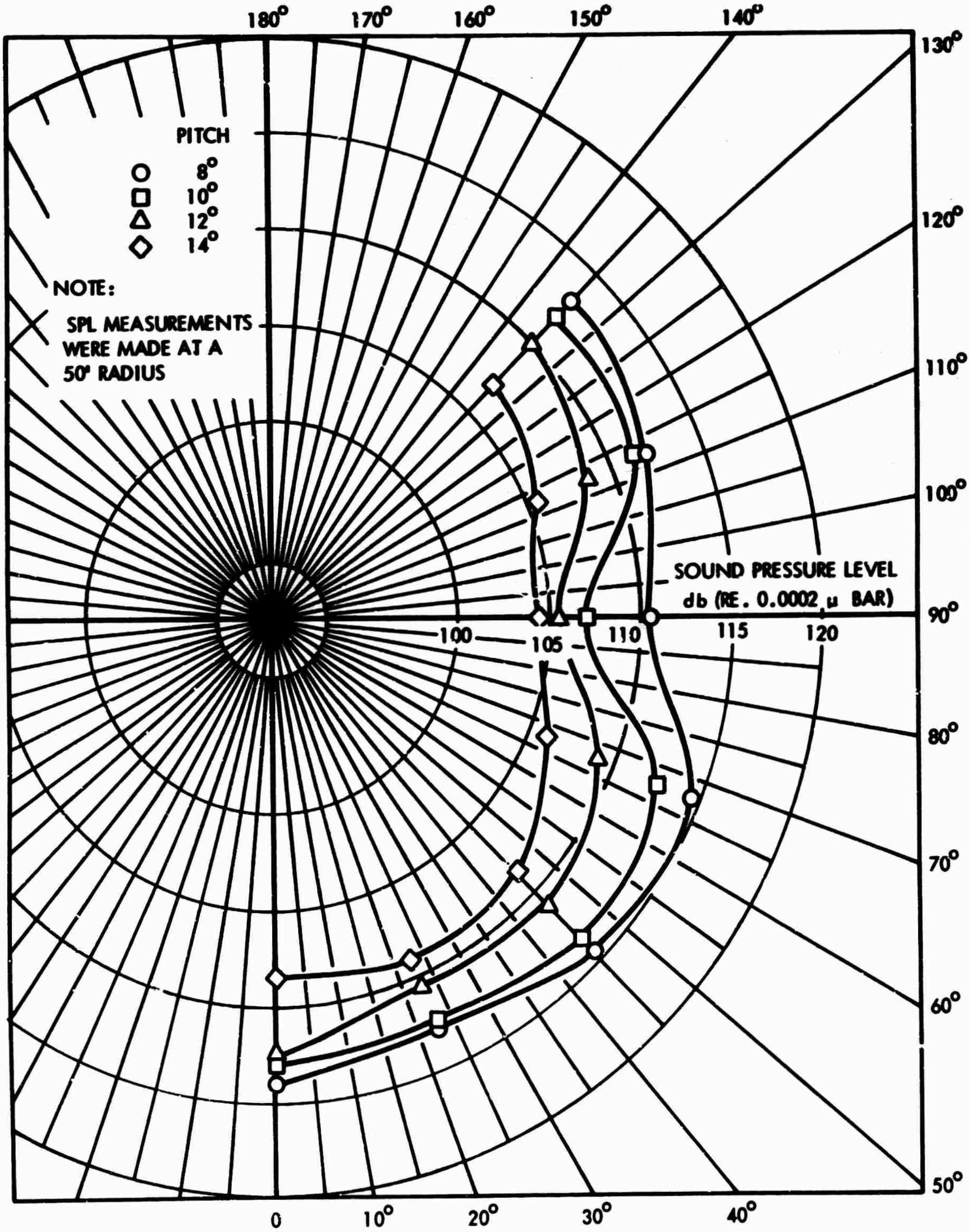


FIGURE 21 - SOUND PRESSURE LEVELS AROUND AIRBOAT USING 8 BLADED PROPELLER WITH SHROUD

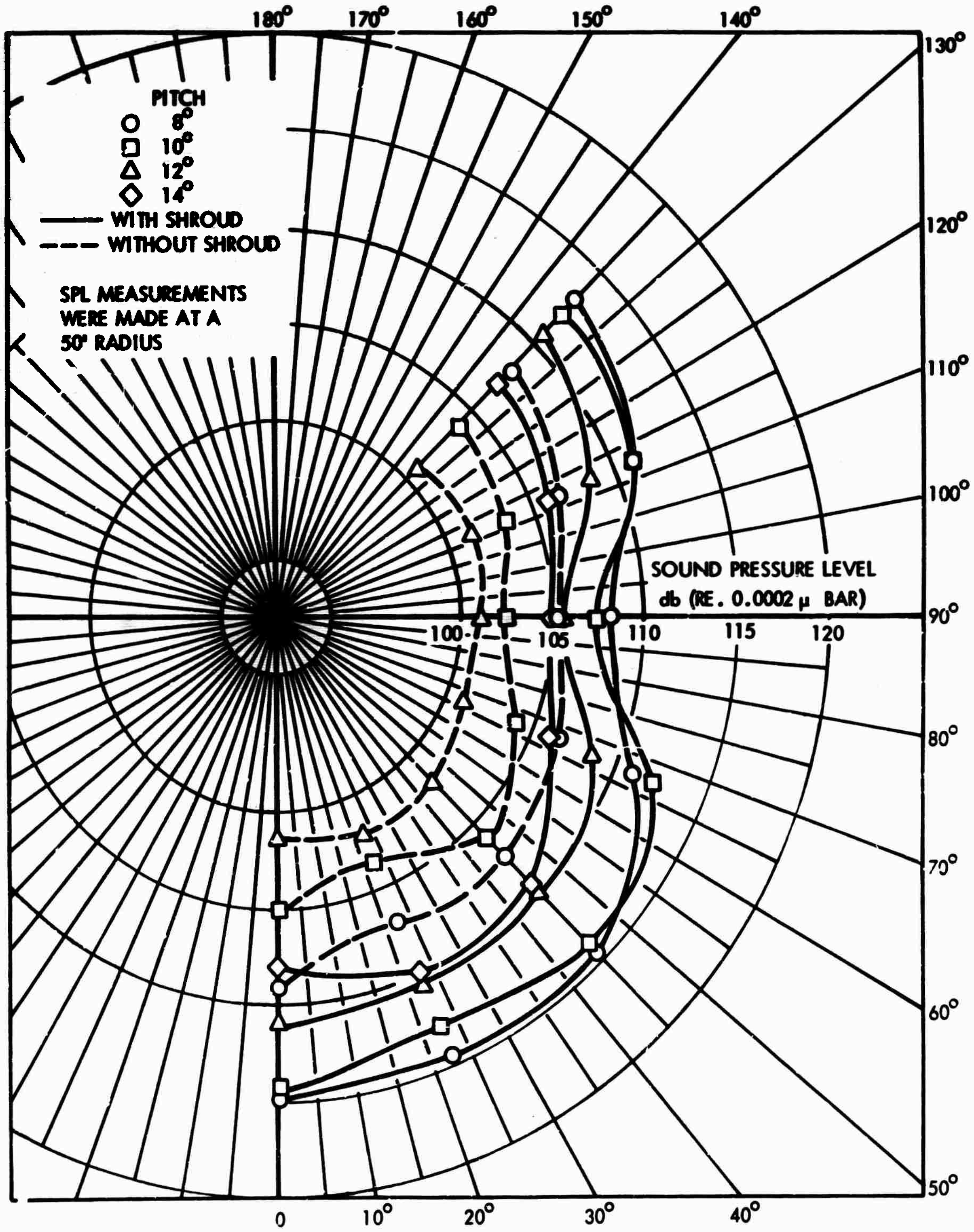


FIGURE 22 - SHROUD PRESSURE LEVELS AROUND AIRBOAT USING 16 BLADED PROPELLER WITH AND WITHOUT SHROUD

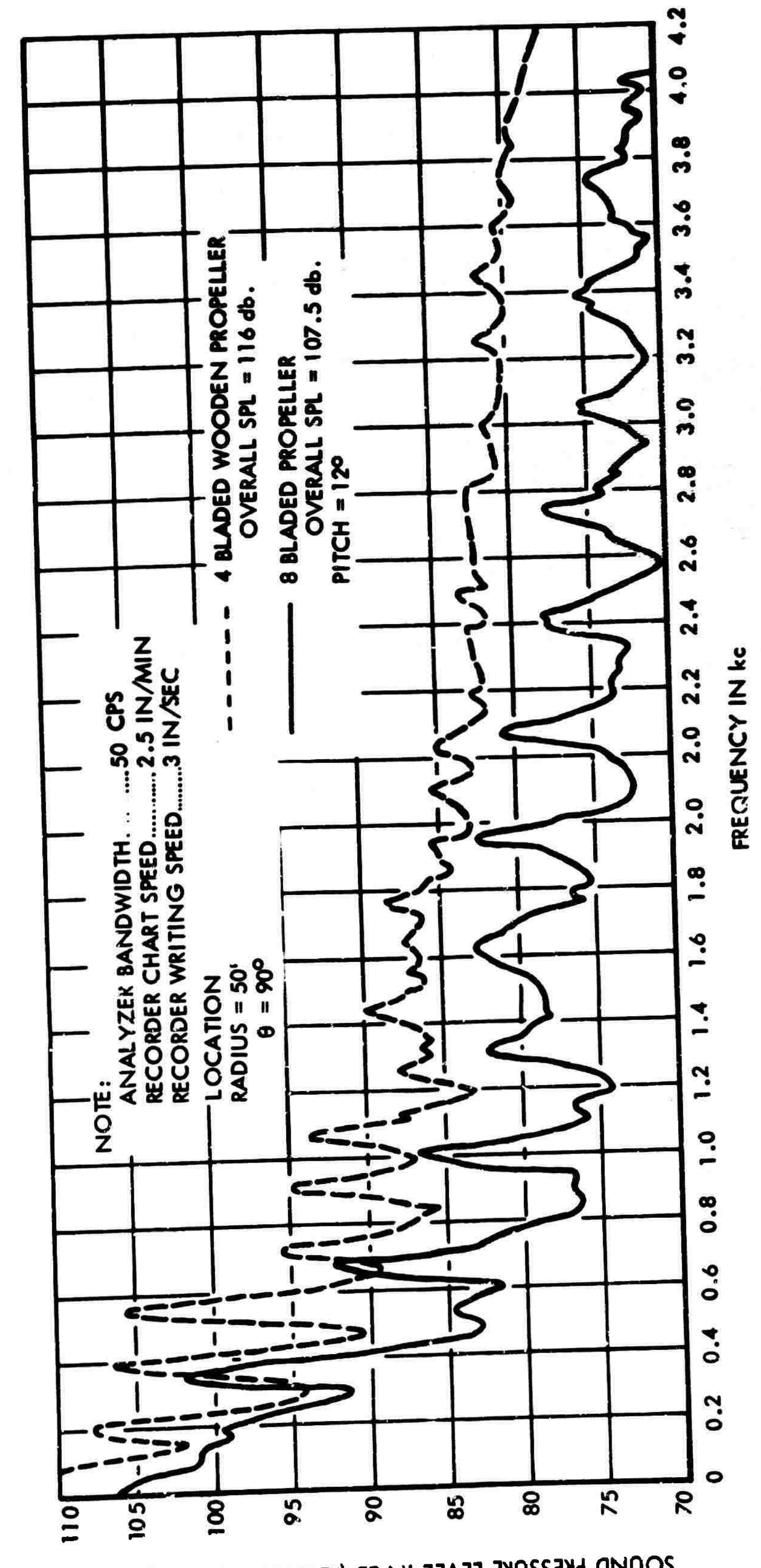


FIGURE 23 - FREQUENCY ANALYSES OF 4 AND 8 BLADED PROPELLERS

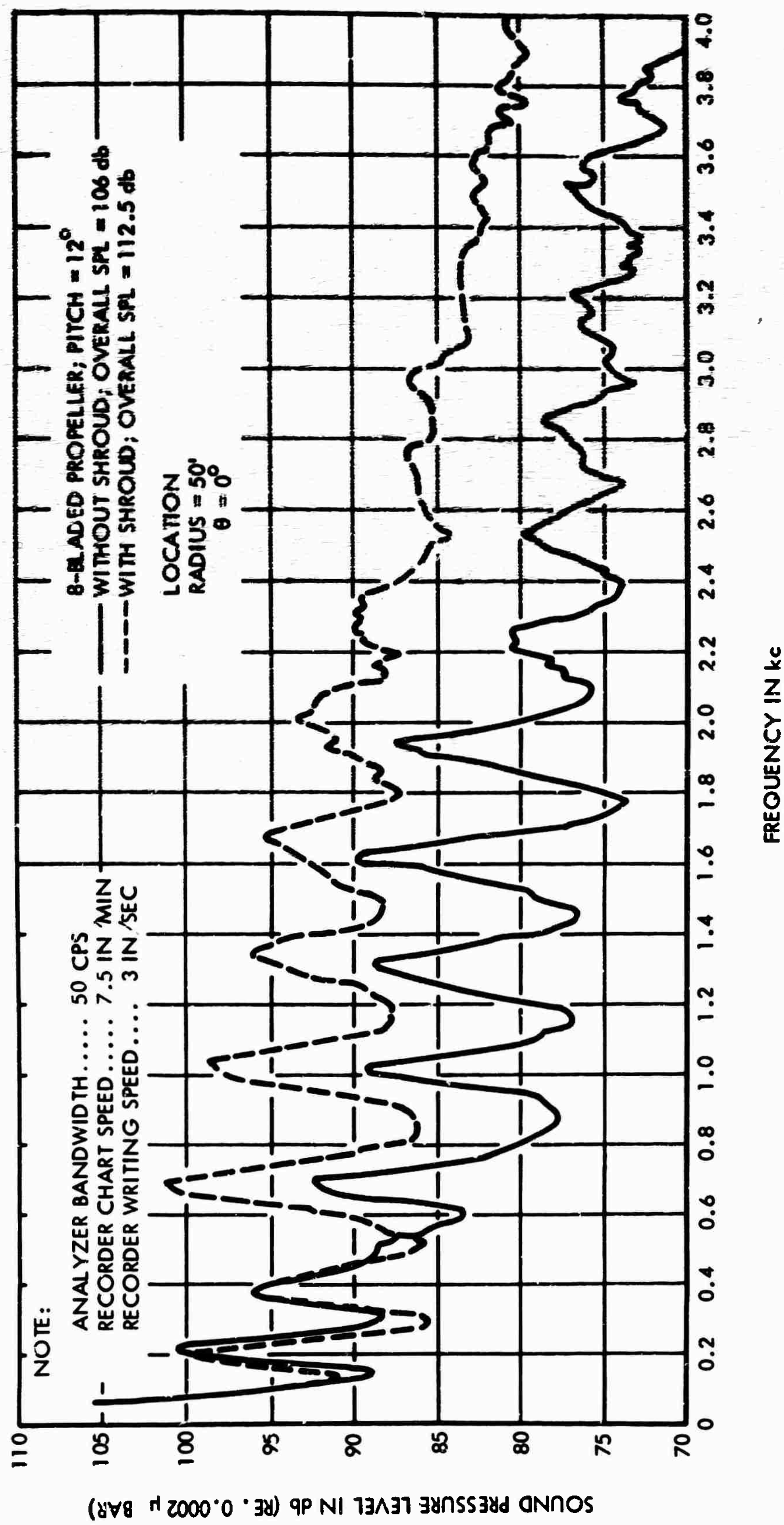


FIGURE 24 - FREQUENCY ANALYSES OF 8 BLADED PROPELLER WITH AND WITHOUT SHROUD

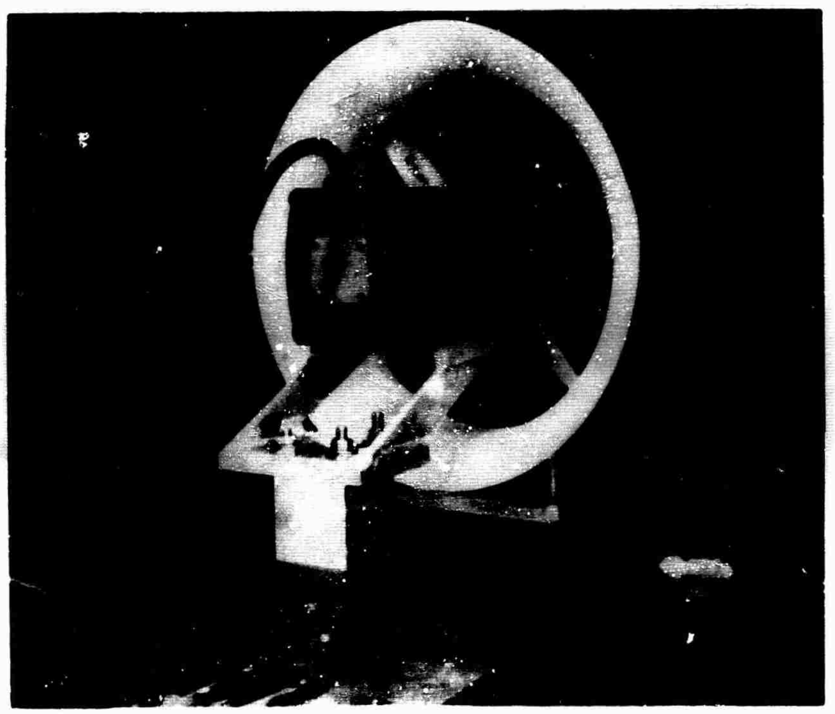


FIGURE 25 - MODEL MOTOR AND NOZZLE MOUNTED ON THRUST DYNAMOMETERS

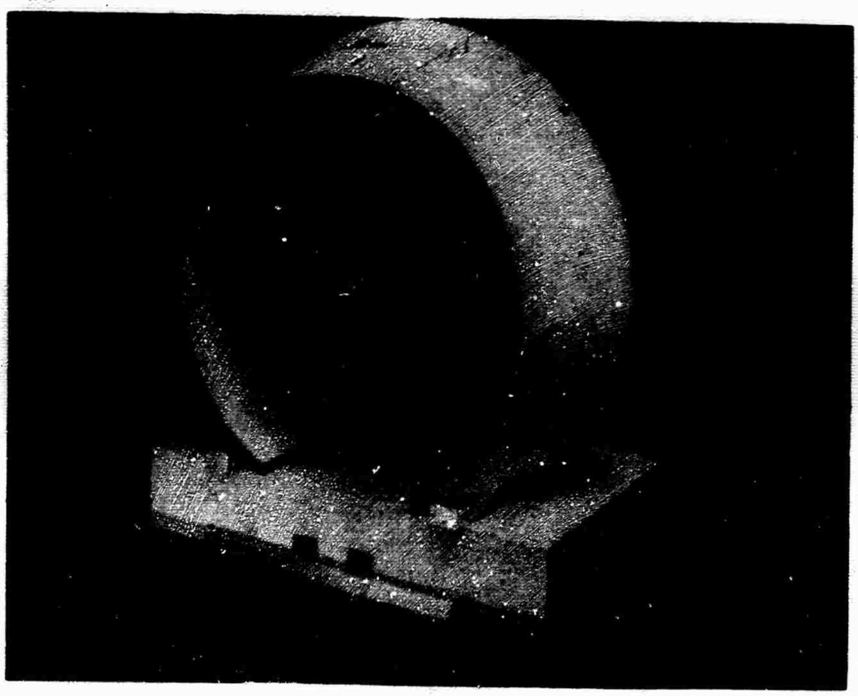


FIGURE 26 - SHROUD WITH SIMULATED BOAT-STERN

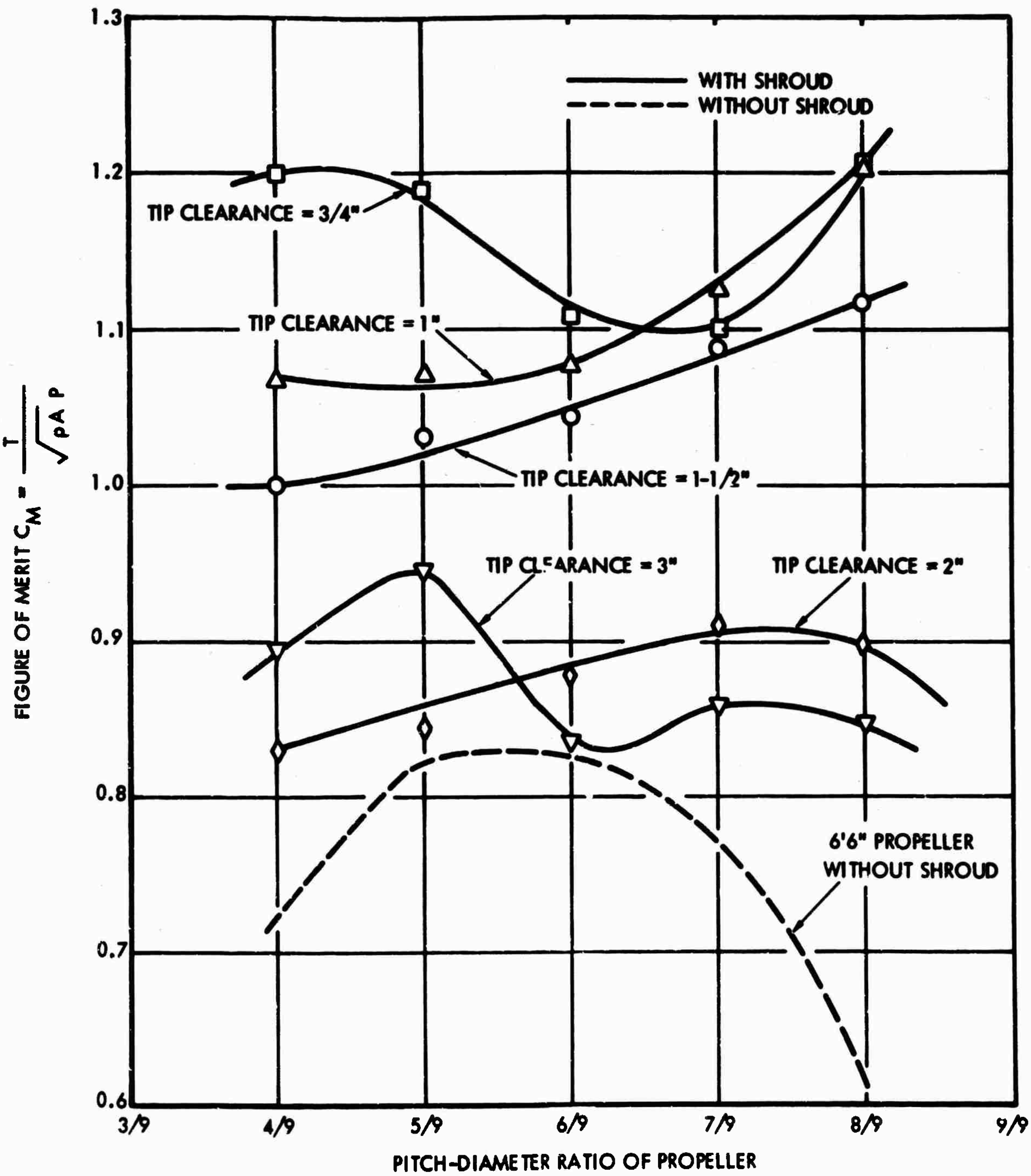


FIGURE 27 - EFFECT OF TIP CLEARANCE ON FIGURE OF MERIT
(RESULTS OF MODEL TESTS)

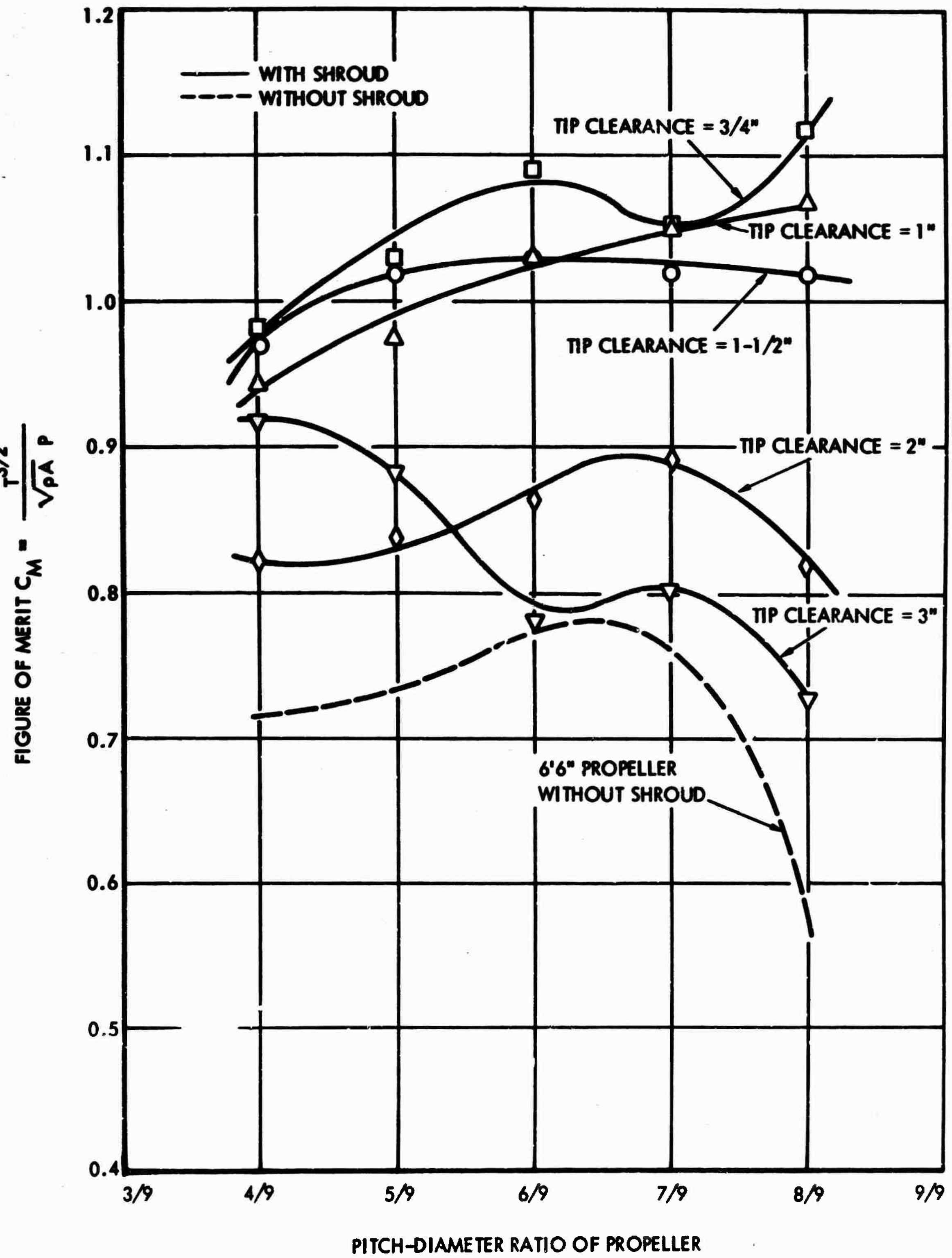


FIGURE 28 - EFFECT OF TIP CLEARANCE ON FIGURE OF MERIT (MODEL TESTS WITH BOAT-STERN SIMULATED)

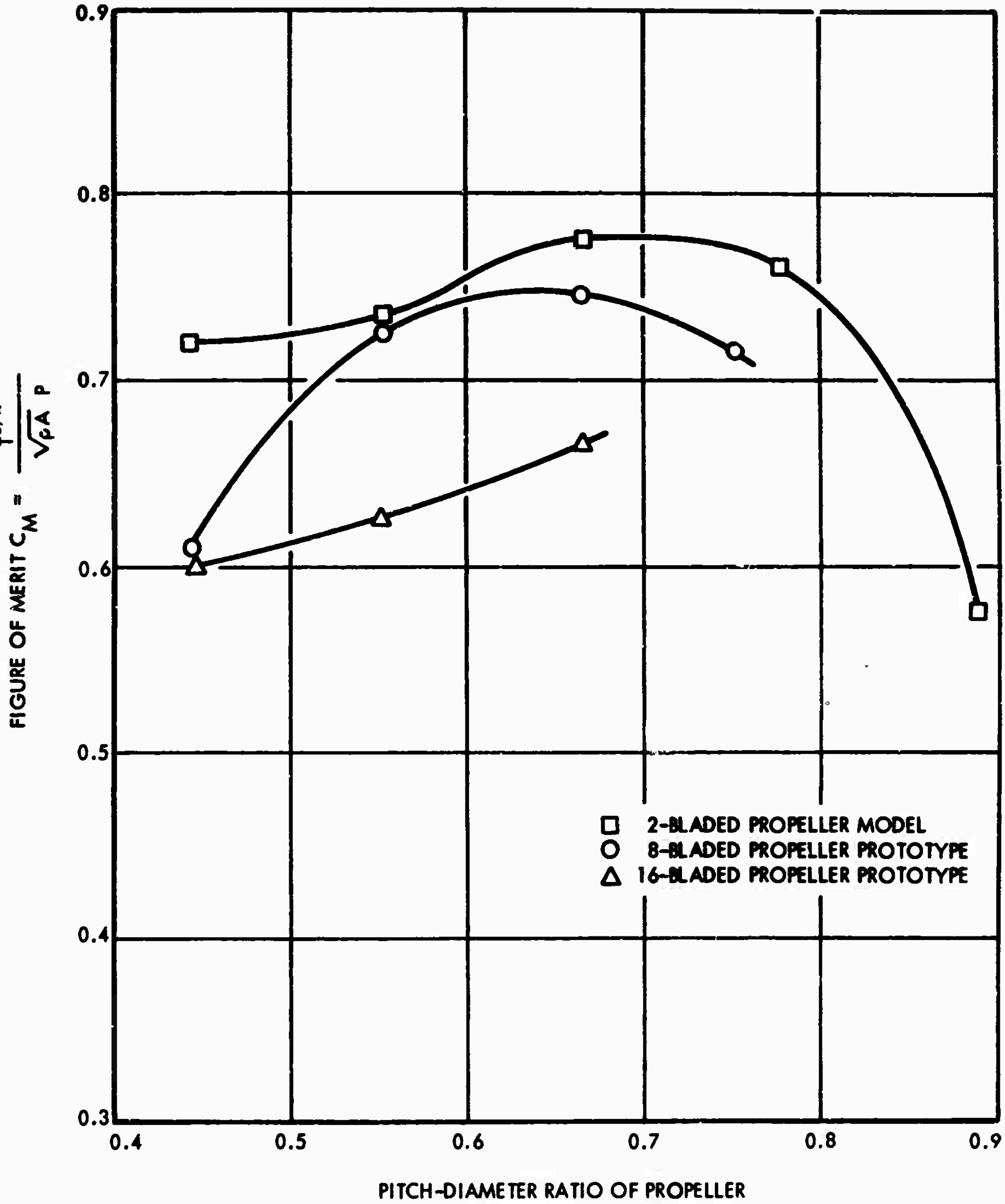


FIGURE 29 - COMPARISON OF MODEL AND PROTOTYPE DATA

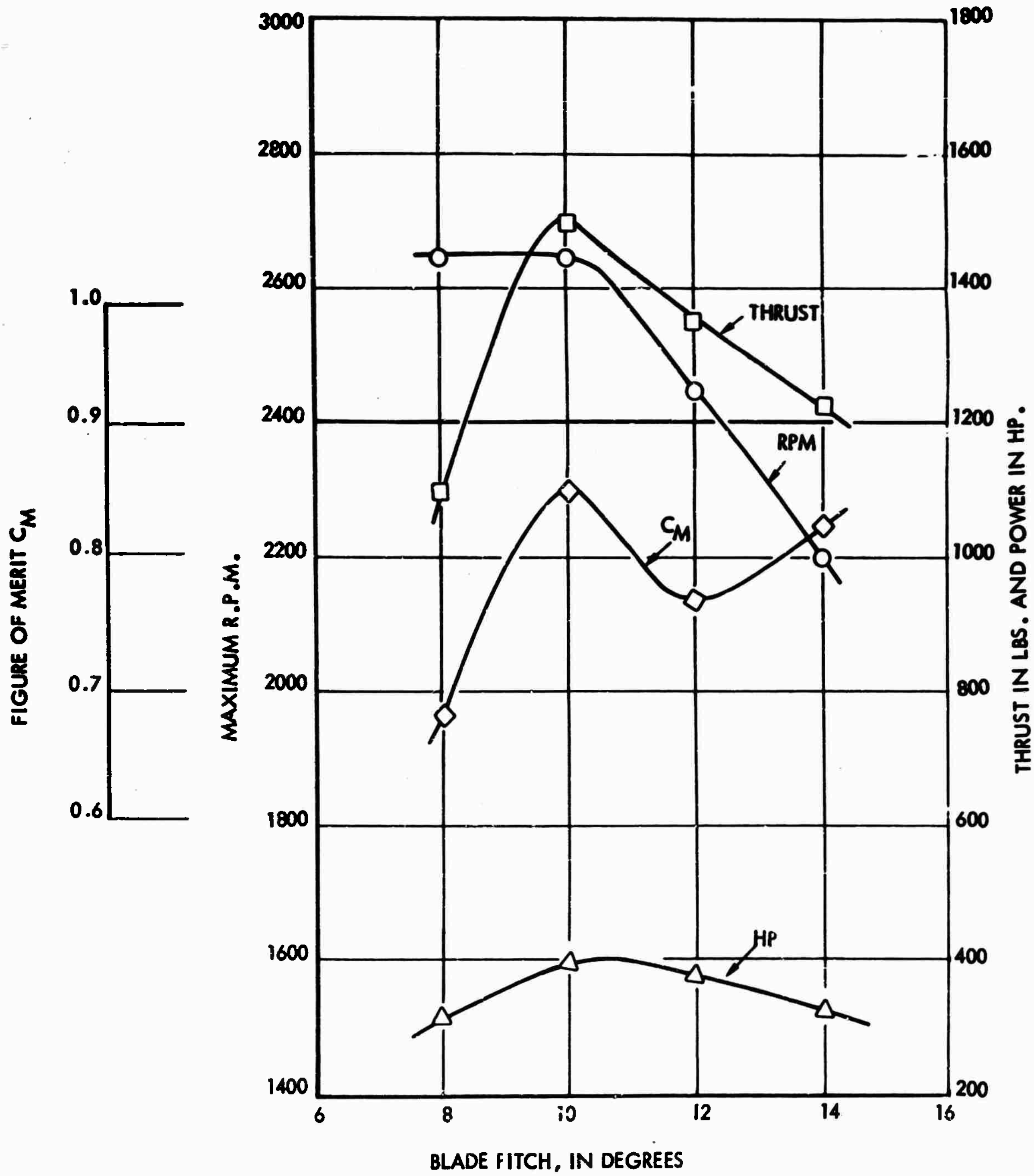


FIGURE 30 - PERFORMANCE OF 8 BLADED 6' 11" PROPELLER WITH SHROUD

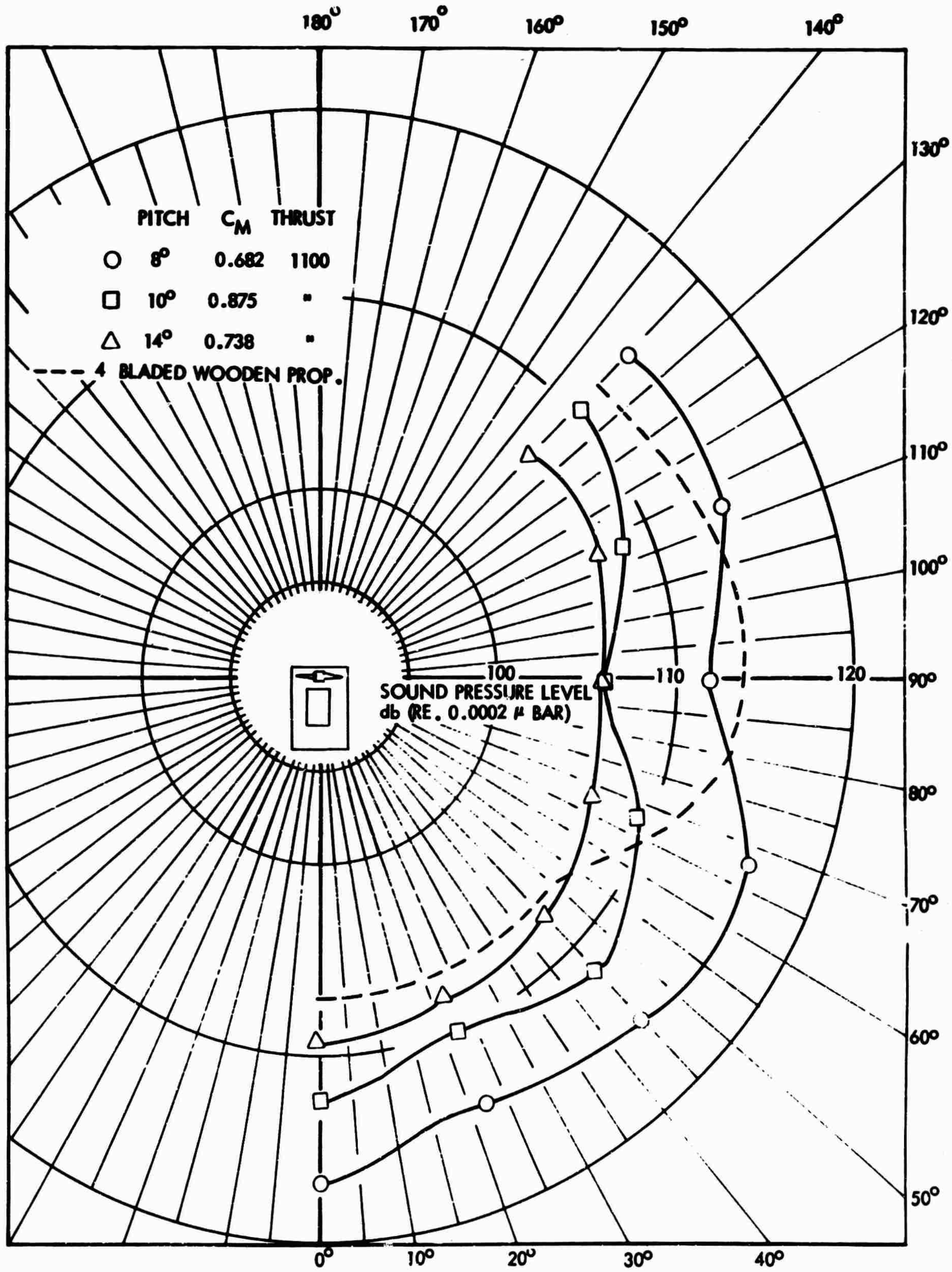


FIGURE 31 - SOUND PRESSURE LEVELS AROUND AIRBOAT WITH 8 BLADED, 6'11" PROPELLER WITH SHROUD

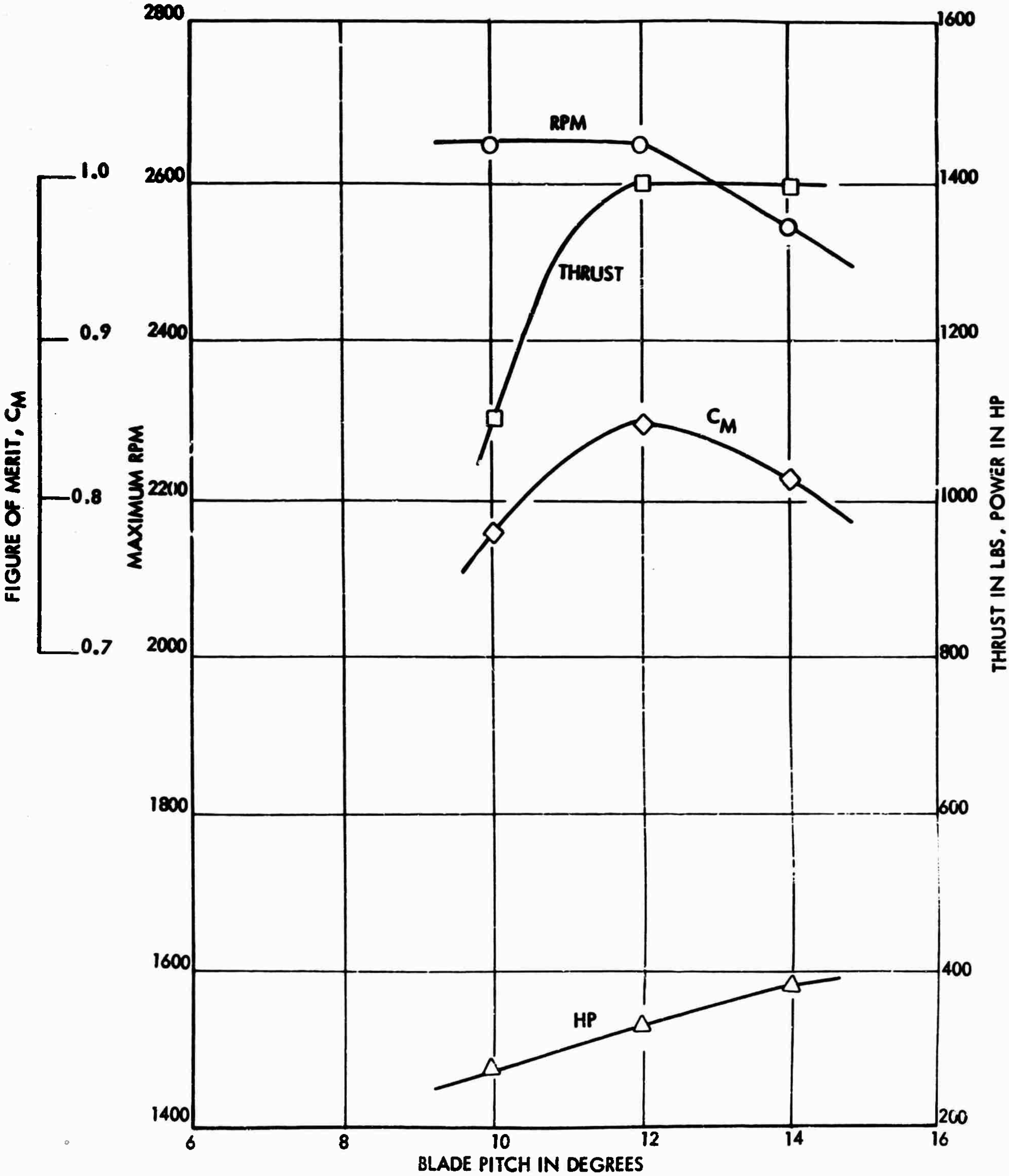


FIGURE 32 - PERFORMANCE OF 4 BLADED, 6' 11" DIAMETER PROPELLER WITH SHROUD

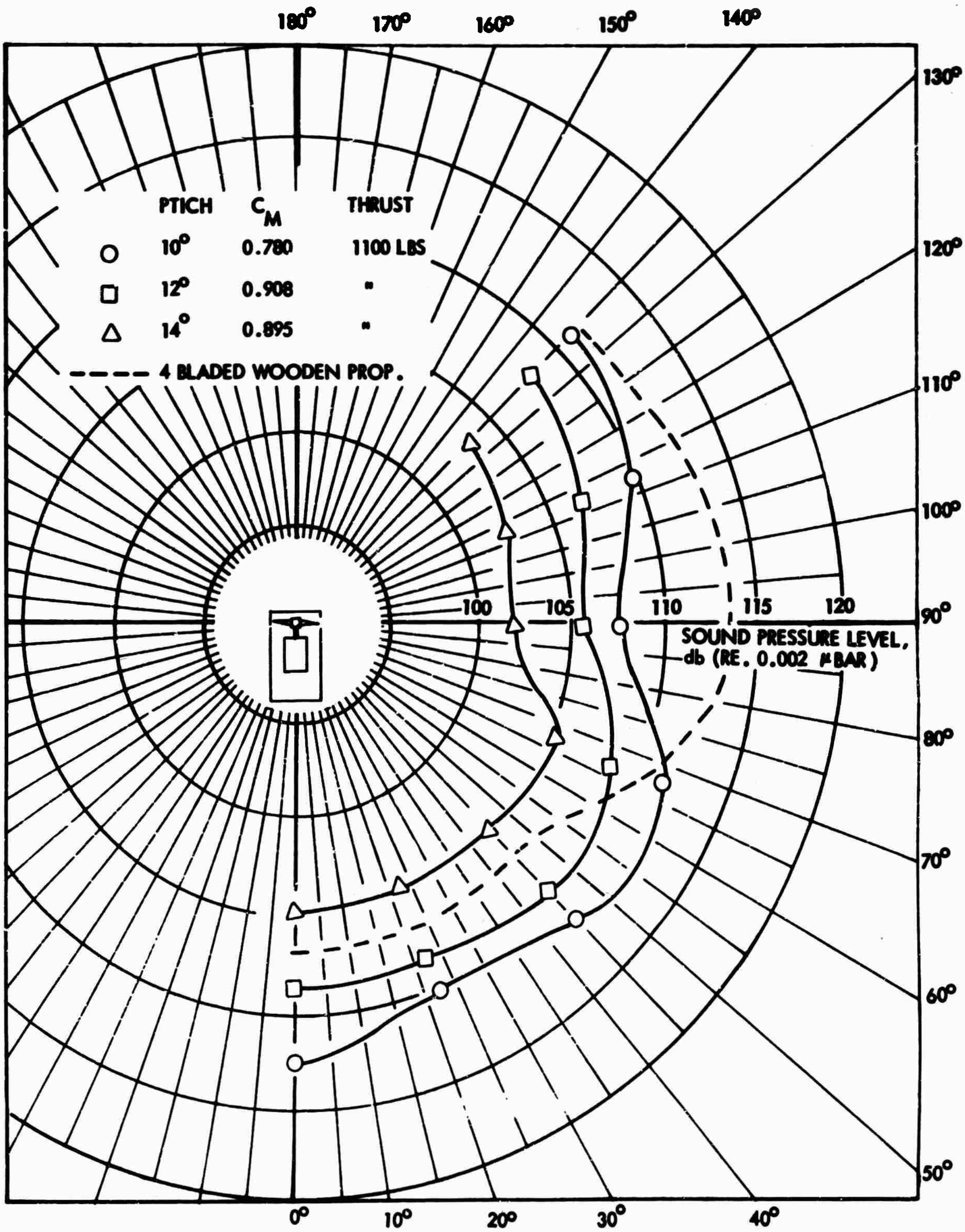


FIGURE 33 - SOUND PRESSURE LEVELS AROUND AIRBOAT WITH 4 BLADED 6' 11 PROPELLER WITH SHROUD

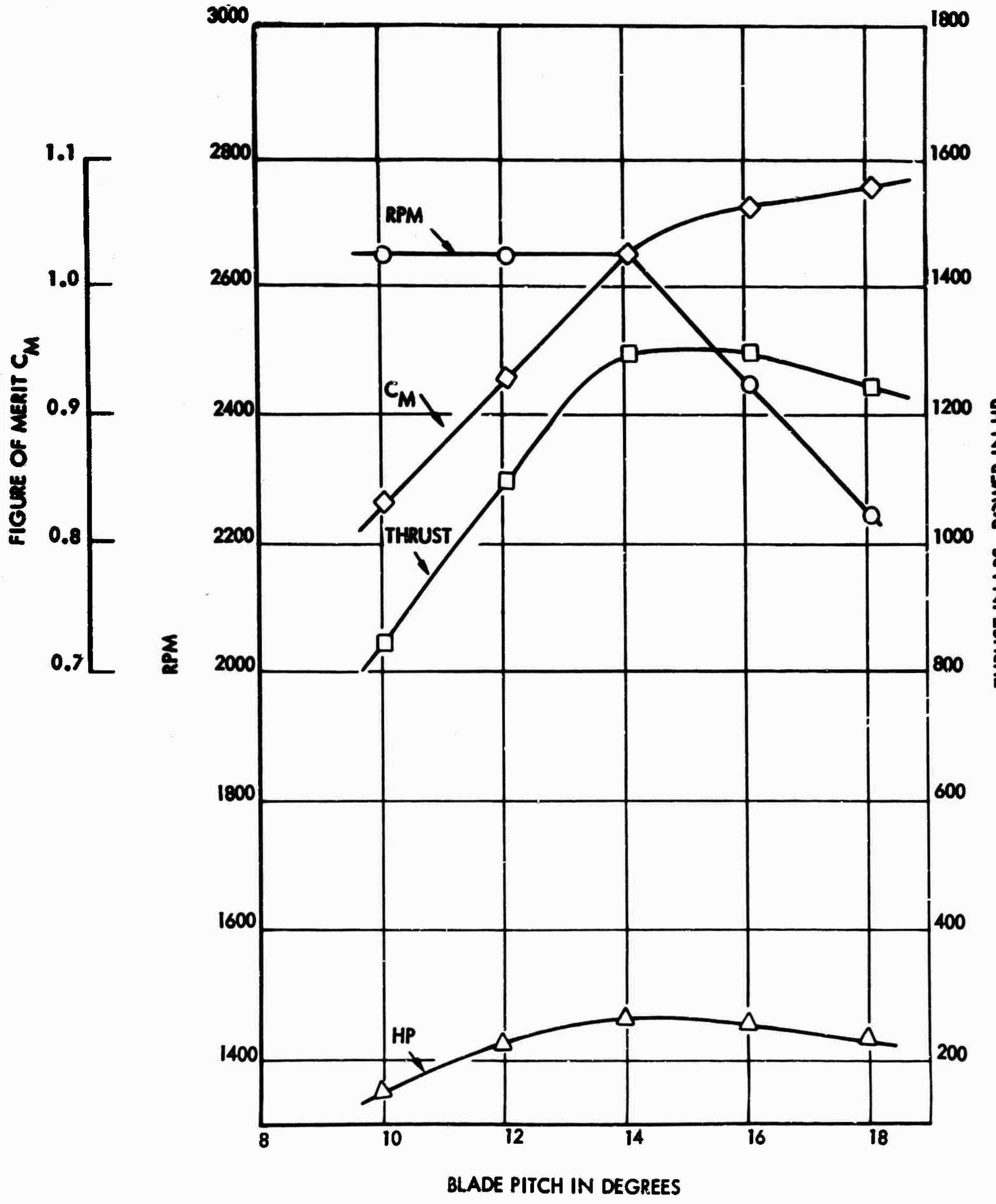


FIGURE 34 - PERFORMANCE OF 2 BLADED 6' 11" PROPELLER WITH SHROUD

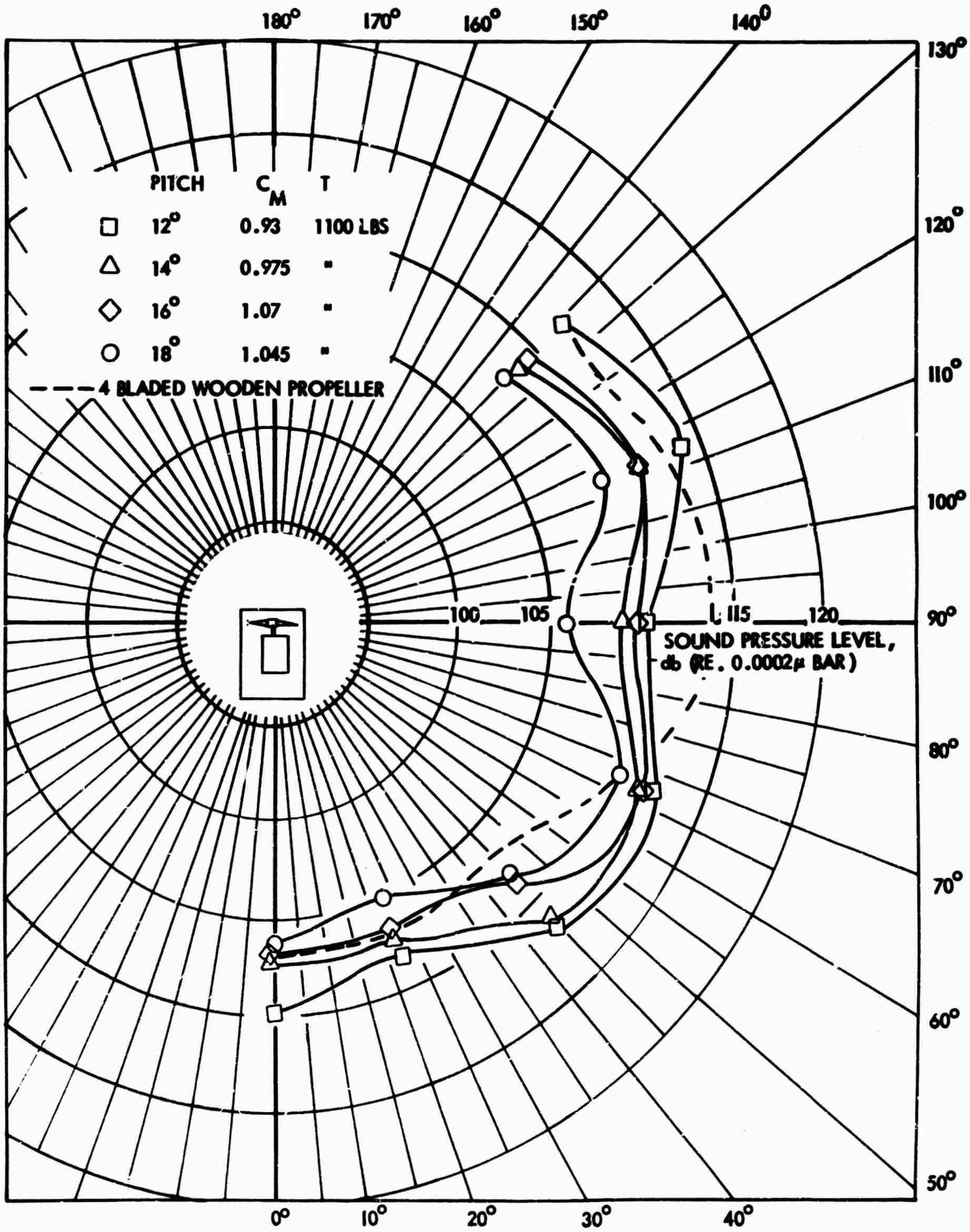


FIGURE 35 - SOUND PRESSURE LEVELS AROUND AIRBOAT WITH 2 BLADED, 6'11" PROPELLER WITH SHROUD

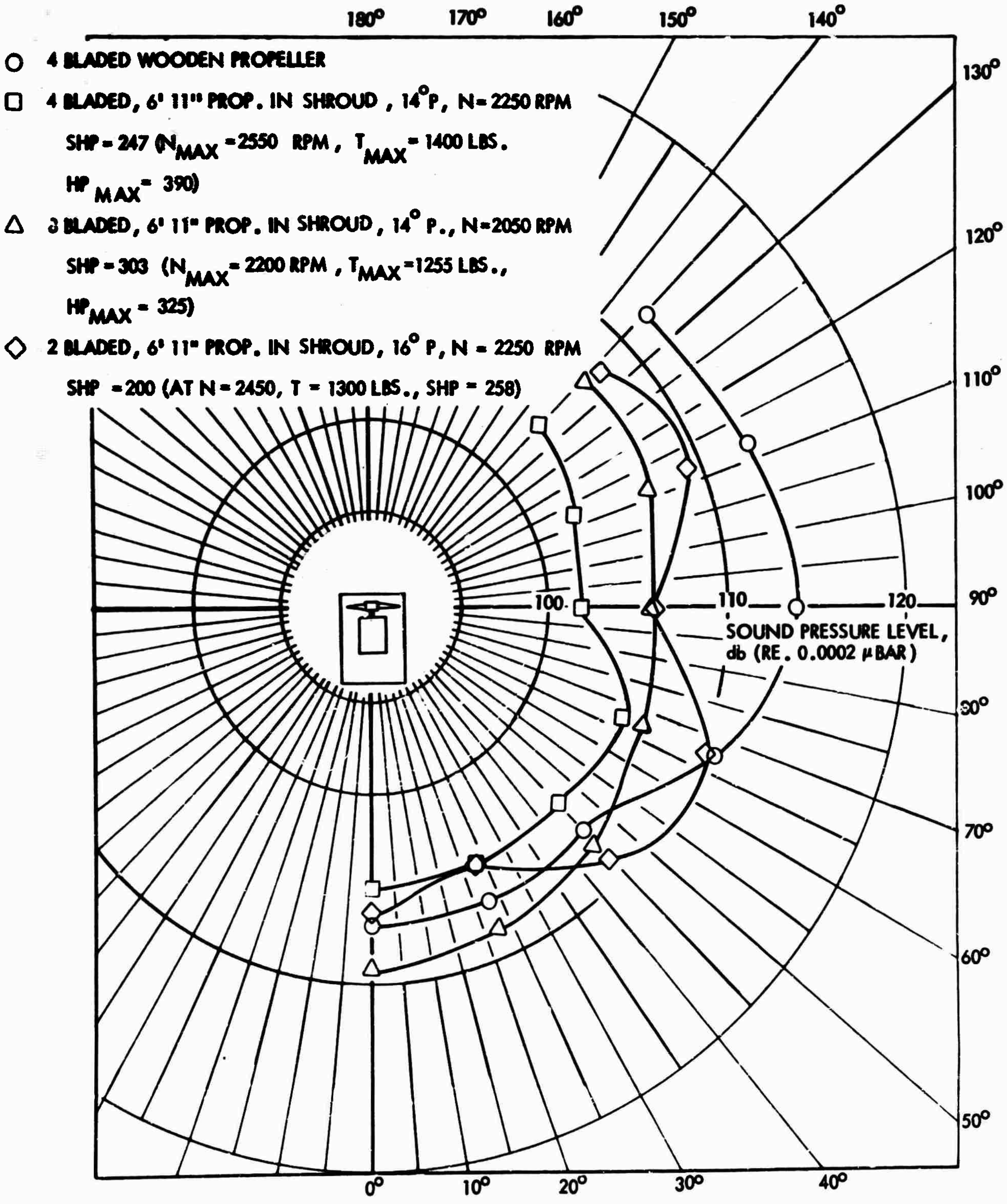


FIGURE 36 - SOUND PRESSURE LEVELS AROUND AIRBOAT WHEN PRODUCING 1100 POUNDS OF THRUST

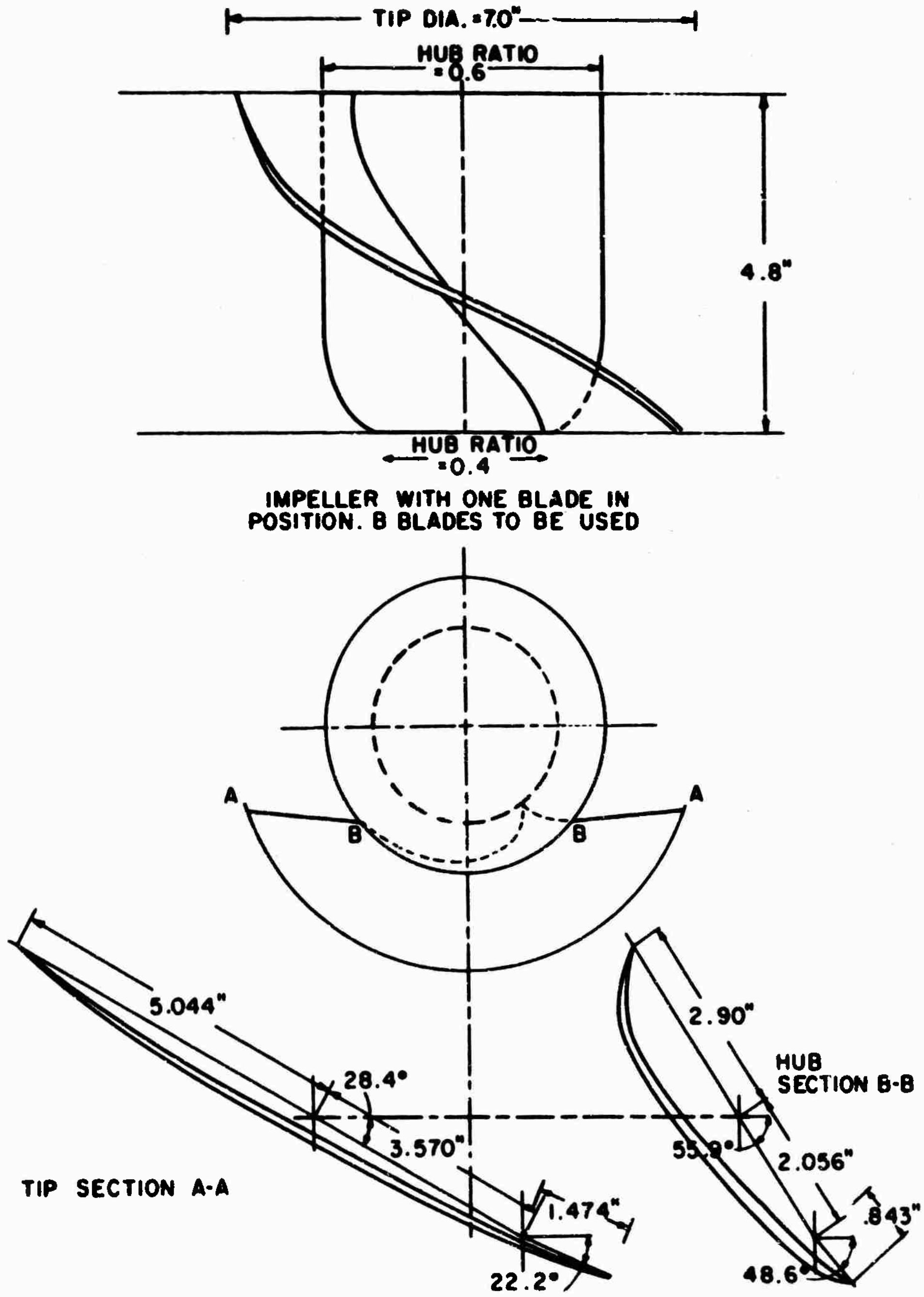


FIGURE 37 - HYDRONAUTICS, INCORPORATED DESIGN OF IMPELLER FOR COMMERCIAL WATER JET SYSTEM

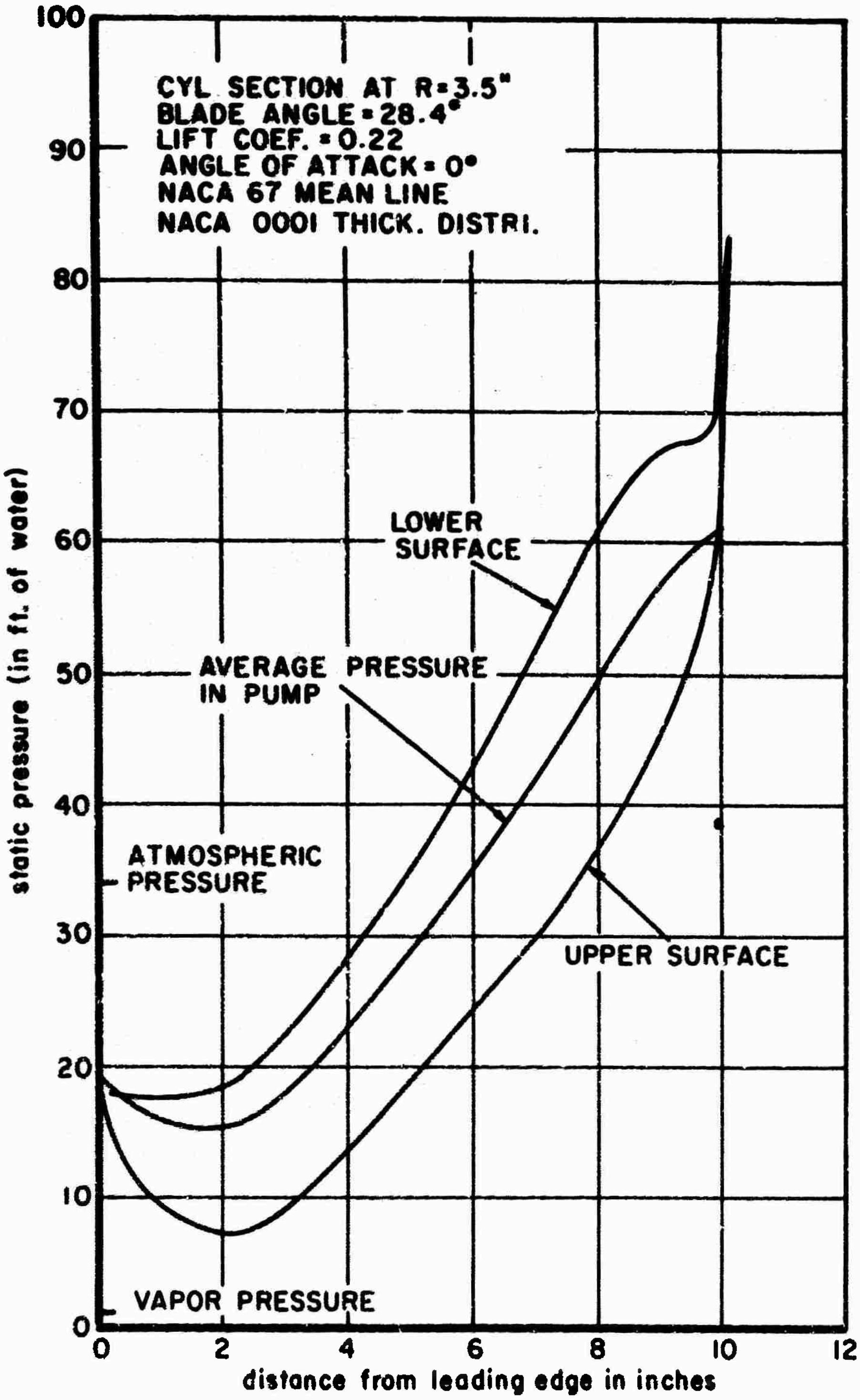


FIGURE 38 - THEORETICAL PRESSURE DISTRIBUTION OVER FOIL AND AVERAGE PRESSURE RISE IN PUMP AT DESIGN CONDITION

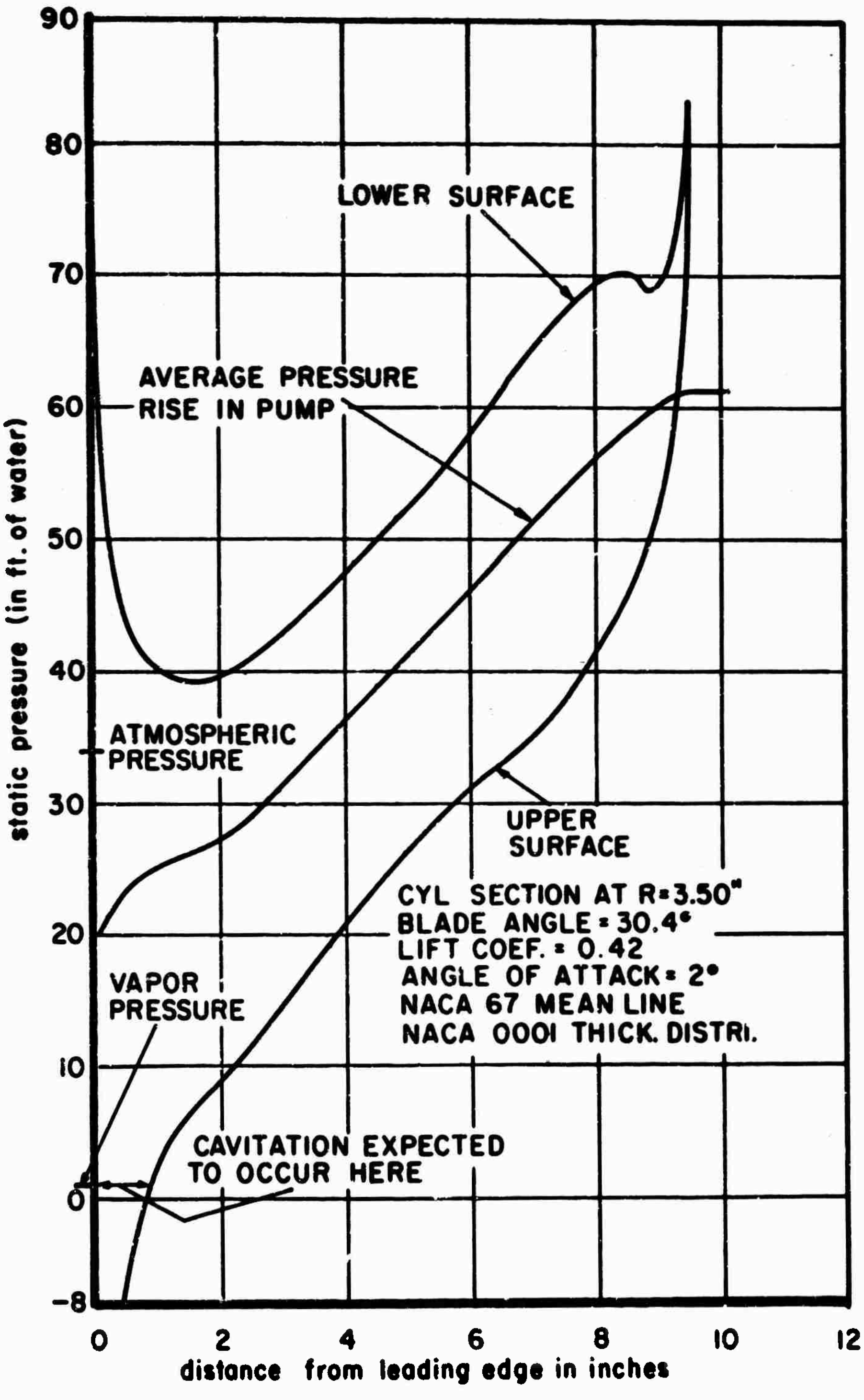


FIGURE 39 - THEORETICAL PRESSURE DISTRIBUTION OVER FOIL AND AVERAGE PRESSURE RISE IN PUMP AT OFF DESIGN CONDITION

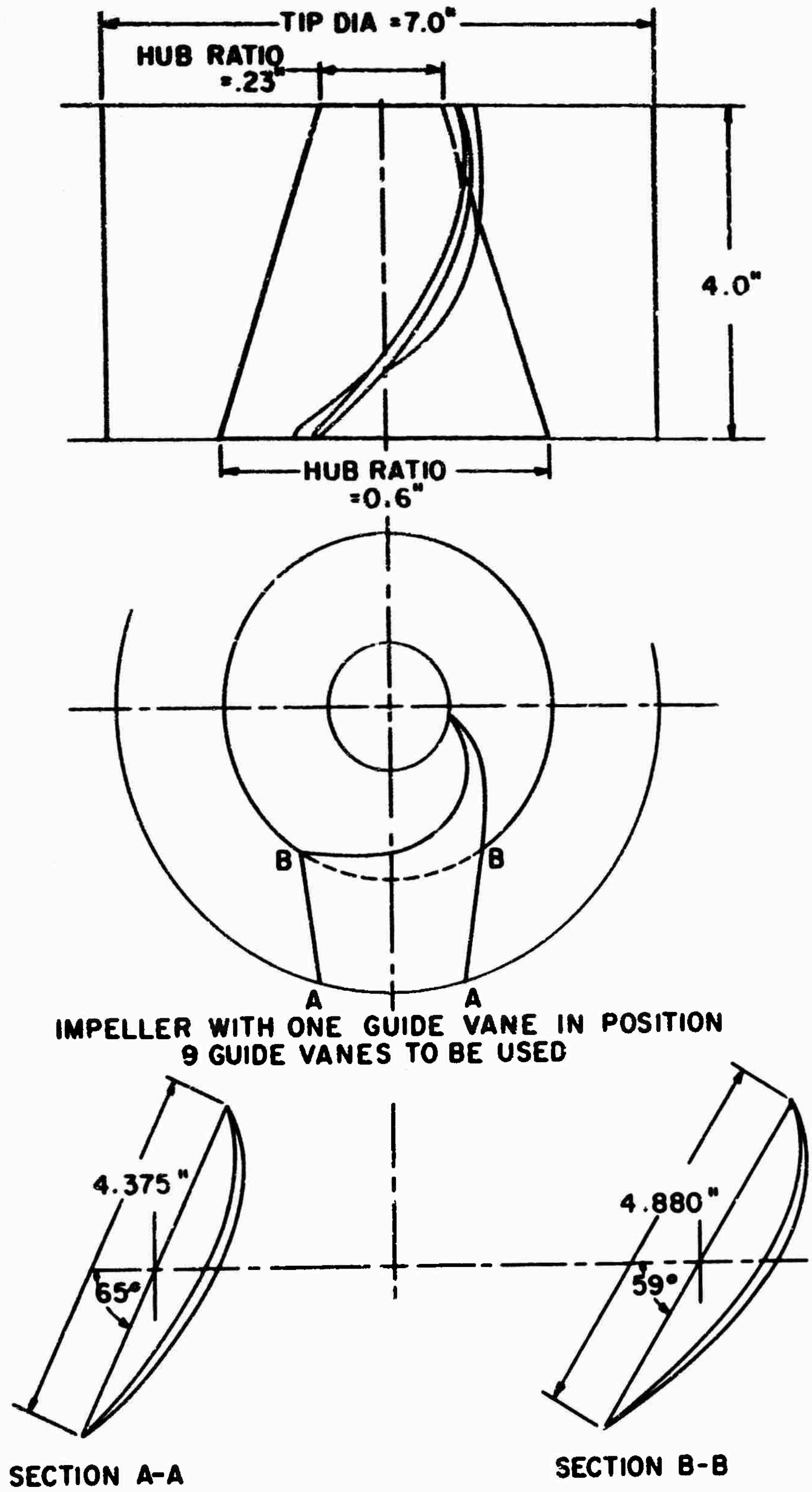


FIGURE 40 - HYDRONAUTICS, INCORPORATED DESIGN OF GUIDE VANES FOR COMMERCIAL WATER JET SYSTEM

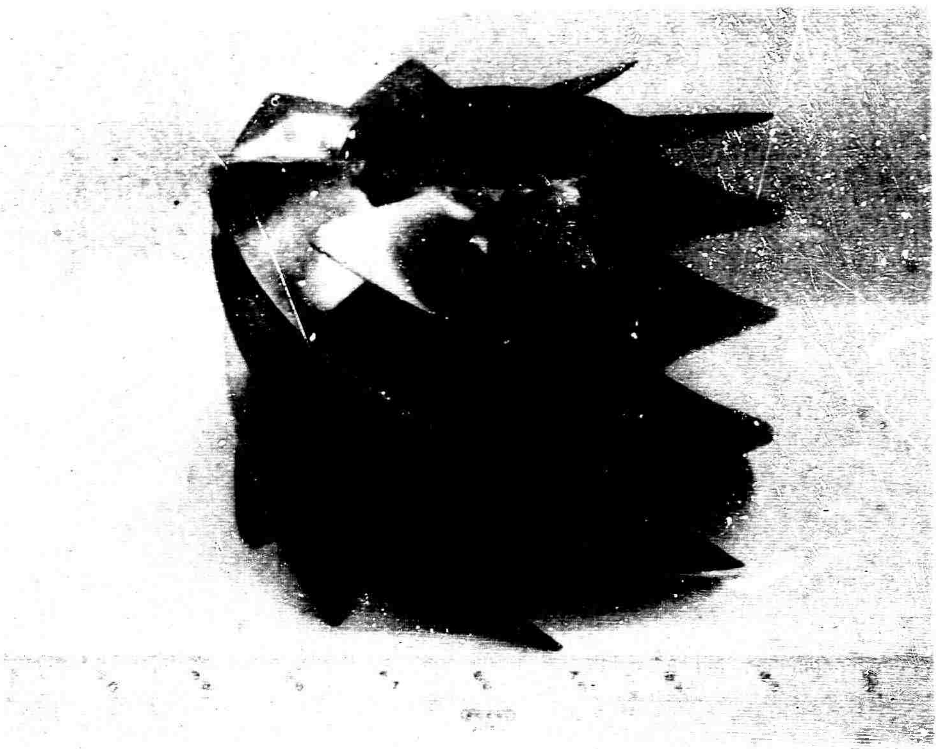


FIGURE 41 - REDESIGNED IMPELLER FOR COMMERCIAL WATER JET SYSTEM

FIGURE 42 - NEW GUIDE VANES FOR COMMERCIAL WATER JET SYSTEM

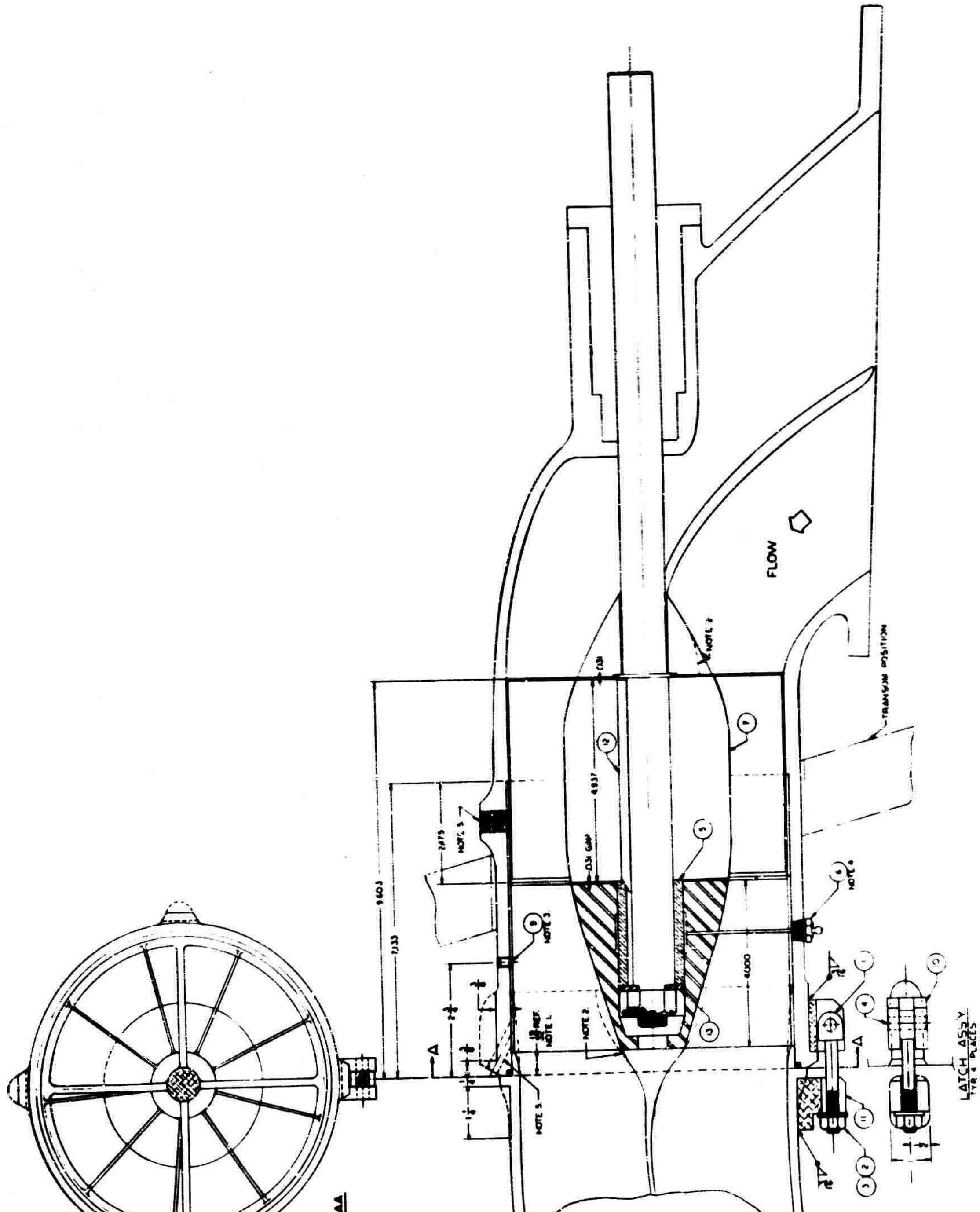


FIGURE 43 - ASSEMBLY OF IMPELLER AND STATOR IN COMMERCIAL WATER JET

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13. ABSTRACT This report deals with problems encountered in two different forms of propulsion used for shallow draft boats. The first part of the report describes the program undertaken to reduce the radiated noise levels around a boat propelled by means of an airscrew. A new propeller was designed to reduce the radiated noise while providing the same or higher thrust. A shroud was designed to reduce the propeller thrust loading and hence decrease the radiated noise level. An extensive series of noise and thrust performance tests was carried out, in which the number of blades and blade pitch were varied. The results of these tests indicated that the new propeller with 4 blades and a 14° pitch, operating in the shroud provided more thrust and was quieter than the original wooden propeller.

The second part of the report concerns the design of impellers for use in water jet propulsion system for shallow draft boats. The impellers in a commercial water jet system used by the Army did not perform as anticipated. The report describes the design of a new impeller and guide vanes to replace those in the commercial unit. It also was designed to develop a maximum head and discharge without cavitation or separation and hence develop maximum thrust. The impeller and guide vanes have been fabricated and installed in the commercial water jet unit.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Pump Impeller Design						
Shallow Draft Boat Propulsion						
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